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THE UNIVERSITY OF OKLAHOMA  
GRADUATE COLLEGE

A STUDY OF THE EFFECT OF VISCOSITY RATIO ON THE  
DISPLACEMENT OF MISCIBLE FLUIDS IN POROUS MEDIA

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the  
degree of

MASTER OF PETROLEUM ENGINEERING

BY

FLOYD  
F. W. COOCH, JR.

//  
Norman, Oklahoma

1949

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\_\_\_\_\_

BY

W. H. HARRIS, JR.  
Professor, Department of Petroleum Engineering

1962

### ACKNOWLEDGMENTS

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Appreciation is also expressed to the Petroleum Engineering Faculty, who helped in editing this thesis and to his fellow workers for their helpful suggestions.

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# RECORD OF THE PROCEEDINGS

DATE	DESCRIPTION	AMOUNT
1891	Jan 1 - Balance forward	100.00
1891	Jan 15 - Received from John Smith	50.00
1891	Jan 20 - Paid for rent	25.00
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1891	Feb 5 - Received from John Smith	50.00
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1891	Jul 15 - Received from John Smith	50.00
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1891	Nov 5 - Received from John Smith	50.00
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# A STUDY OF THE EFFECT OF VISCOSITY RATIO ON THE DISPLACEMENT OF MISCIBLE FLUIDS IN POROUS MEDIA

## CHAPTER I

### INTRODUCTION

Within recent years the increasing demand for petroleum products and the realization that the supply of new sources of petroleum is not inexhaustible have focused attention on the fact that in most of our oil production in the past, only about one third of the oil originally present in the reservoir is recovered when the economic limit is reached. This figure applies only when the field is produced by conventional methods where the main source of energy is the gas dissolved in the oil.

With this in mind many investigators have sought to find ways both to remove the residual oil and to improve methods of production so that a much greater per cent of the oil is removed initially.

Two methods are in common use today to remove the residual oil after primary depletion. Both of these methods involve displacement of the residual oil by another fluid. In one method gas and the other method water is used as the

and in some instances the subject has been treated in a

very different manner to that of the original work.

## THE AUTHOR

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THE AUTHOR has been very much interested in the

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displacing fluid. Although both of these methods have been applied in the field for a number of years and much laboratory work has been done on the displacement of oil by another fluid in a porous media, there still remains a large number of problems to be solved before the mechanics of displacement of fluids in a porous media is completely worked out. Many investigators are now working on these problems with the idea of gaining more complete recovery of petroleum from the reservoir.



## CHAPTER II

### REVIEW OF PREVIOUS INVESTIGATIONS

The initial study of flow of liquids through sands dates back to 1800 when H. Darcy (1) performed his experiments on the flow of water through sand. In 1888 King (2) measured the rate of flow of water and air through consolidated and unconsolidated sands and published the results. It was not until 1900, when the increasing demand for oil caused the U.S. Bureau of Mines to make a series of experiments on flow characteristics of oil and water, that additional work was done on flow of fluids in a porous media. By 1930 the importance of flow measurements to production of gas and oil was realized and in the ensuing years the investigations of Reed (3), Fetting (4), Wyckoff, Botset and Muskat (5), and many others added materially to our knowledge of fluid flow in porous media.

In the last ten to fifteen years most of the work has been directed toward the development and improvement of methods of predicting petroleum reservoir performance. As a result there have been numerous investigations made of the behavior of immiscible fluids in porous media. Leverett (6),

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\*Numbers in parenthesis refer to references in the bibliography.

THE UNITED STATES OF AMERICA

IN SENATE

January 1, 1900

REPORT OF THE

COMMISSIONER OF THE GENERAL LAND OFFICE

FOR THE YEAR 1899

IN RESPONSE TO A RESOLUTION OF THE SENATE

PASSED MAY 1, 1898

AND A RESOLUTION OF THE HOUSE OF REPRESENTATIVES

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Leverett and Lewis (7), and others have contributed much to the development of the theory and mechanics of the displacement of oil by water. Information concerning the displacement of oil by gas was reported by several investigators such as Reid and Huntington (8), Baker (9), and Hurler and Leverett (10). The latter worked out a satisfactory picture of the mechanics of the displacement of oil by both water and gas.

However, while the above work was being carried out with immiscible fluids, little work was done on the mechanics of displacement of two miscible fluids. Korte (11) and Dwyer (12) investigated the effects of specific gravity, velocity and pressure on the amount of mixing taking place during the displacement of one gas by another in unconsolidated sand. They concluded that the amount of mixing was inversely proportional to the rate of flow and that it became less as the pressure was increased up to a certain point for any given linear velocity. Above this point an increase in pressure caused an increase in the amount of mixing. Their experiments also indicated that less mixing took place when the heavier gas was used as the displacing fluid.

Bassett, Morgan and Whitel (13) in studying the wettability of interstitial pores arrived at some conclusions concerning the displacement of water by water in a consolidated sand. Their results in all cases showed that after injecting into the core a volume of displacing water equal to one pore



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### CHAPTER III

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#### STATEMENT OF PROBLEM

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This problem was undertaken to study the displacement of one fluid by another elastic fluid in a porous media, as in all problems of fluid displacement there are several variables involved. These factors are:

- (1) Physical characteristics of the porous media
- (2) Chemical characteristics of the porous media
- (3) Viscosity of the fluids
- (4) Specific gravity of fluids
- (5) Differential pressure or rate of displacement

Since the experiment was undertaken primarily to obtain information of a fundamental nature it was thought best to vary only one factor and to maintain all other factors constant. When it became evident during the course of this investigation that the force of gravity was affecting the results due to the displacement taking place with the core in a horizontal position, a series of similar drives were made with the core in a vertical position to determine the magnitude of the gravity effect.

This investigation was prompted by the fact that





## CHAPTER IV

### INTRODUCTION

The synthetic core that was used in this work consisted essentially of pure quartz grains partially consolidated by silicon. This core was contained in a cylindrical Lucite tube, 100 centimeters in length and 6.34 centimeters inside diameter.

To make this core fill Creek sand, obtained from an outcrop near Sulphur, Oklahoma, was sieved and a fraction between 60 and 140 mesh retained. This sand was thoroughly washed with hot water then cleaned by agitation in hot hydrochloric acid. Following this it was again washed with water then agitated in a hot sodium hydroxide solution with a final wash with water until the solution was shown by litmus paper to be neutral. The sand was then placed in an oven to be dried. After drying was complete the sand was re-sieved with the 60 to 140 mesh fraction again retained.

Next the Lucite tube was fitted with spacers and plate cut from one piece about 1/16 inch. A circular groove 3/16 inch deep, 6.34 centimeters inside diameter, and 5.75 centimeters outside diameter was machined in the face of each block and

## THEORY

### INTRODUCTION

The purpose of this study is to investigate the effect of the independent variable on the dependent variable.

The study was conducted in a laboratory setting. The independent variable was manipulated at three levels: low, medium, and high. The dependent variable was measured using a standardized scale.

RESULTS

The results of the study are presented in the following table.

Table 1. Mean scores for the dependent variable at different levels of the independent variable.

As can be seen from the table, the mean scores for the dependent variable increase as the level of the independent variable increases. This suggests a positive relationship between the two variables.

The results of the study are consistent with the hypothesis.

DISCUSSION

The findings of this study have several implications.

First, the results suggest that the independent variable has a significant effect on the dependent variable. This finding is important for understanding the relationship between these two variables in other contexts.

a hole drilled was tapped for 3/8 inch threads in the center. Brass fittings and valves were inserted into these holes and a 100 mesh screen placed over the hole. The four corners of the end to bottom rods were drilled to accommodate the rods. Next a compressed rubber gasket was put into the groove of one end plate and the two rods were placed in opposite corners. This plate was fitted to one end of the Lucite tube, the two tie rods being secured at the other end in a wooden block placed on the Lucite tube. Prior to putting on this block a 3 inch extension of the same diameter tube was placed on the end of the long tube. The block left this end of the tube partially open. The tube was then placed on a vibrating table in a vertical position with the end plate down and a length of rubber hose run from the brass fitting to a large beaker.

With the valve at the lower end closed Cytex,\* a colloidal suspension of silica in water, was poured into the top of the tube until there was approximately 3 inches of Cytex in the tube. The closed end was placed in a funnel which was clamped above the vertical tube. This allowed the sand to be fed slowly into the tube. Additional Cytex was added to maintain its level approximately 3 inches over the sand as it was deposited into the bottom of the tube. This method was used to get uniform porosity and permeability in the sand.

When the sand had been deposited even with the top of the long tube, the vibrating table was stopped, the tie rods

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\*Obtainable from the Monsanto Chemical Co., Boston, Mass.





located and the extension tube removed. The slider and plate was put on and all four tie rods were drawn tight and plates sealed and pulled tight, thus sealing both ends of the tube. With the core still in the vertical position the valve on the lower end was opened and the liquid drained out. Then dry air was forced into the top and passed down through the sand and out the lower end of the tube thus displacing any remaining water and drying out the sand. After twenty-four hours of drying with air, the bottom valve was closed, a vacuum pump attached to the top of the tube and a vacuum placed on the tube for twenty-four hours. At the end of this time approximately 1000 cubic centimeters of alcohol ("95%") was forced into the tube through the lower end. The core was again dried by passing dry air through it for a period of forty-eight hours and then maintaining a vacuum on it for twenty-four hours.

The above procedure resulted in a partially desaturated core of essentially pure silica. At this time a series of permeability tests were run with air on the core. These indicated an average overall permeability of 3.4 darcies. However, upon installing pressure taps every 33.3 centimeters along the core it was found that one end of the core had a low permeability compared to the other two sections. A piece 3.3 centimeters long was removed from this end of the core and air permeabilities again run. The overall permeability was found to be 3.32 darcies and none of the sections deviated more than 5 per cent from this value. Since this gave a

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fairly uniform core it was deemed satisfactory for the experiments to be run on it.

The porosity of the core was determined next. The first method was to measure pressure at two different points and record the volume removed in going from the higher to the lower pressure. By using the perfect gas law the porosity was calculated to be .557. The other method was by the use of wet and dry weights. The fractional porosity in this case was calculated to be .567. This latter value was used in all calculations since it was felt that the method used in calculating this value was far more accurate.

The sugar solutions used in this work were made with distilled water and commercial cane sugar (sucrose). The index of refraction of the distilled water was checked before the addition of the sucrose, then after addition of sucrose the index of refraction was again taken and from this information the per cent of sucrose in the solution was calculated and thus the viscosity known.

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## CHAPTER V

### EXPERIMENTAL APPARATUS

With the core partially consolidated and its permeability and porosity judged sufficiently homogeneous for this experiment, additional holes were drilled and tapped in the top of the end plates and brass fittings were installed. With the core in the horizontal position, a wye spigot was installed at the outlet end, and a brass tee installed at the inlet end. With brass valves installed on both sides of the tee a means was provided for purging the fluid system before it entered the core. Hammer tests were connected to the fittings on both end plates.

Next a 1½ liter pyrex bottle with a bottom outlet was set up with a rubber stopper that had a hole in the center through which a copper tube extended into the bottle to a point near the bottom of the bottle. The tube and stopper were held in place by a metal fitting fastened to the bottle by fine copper wire. A brass tee was connected to the tubing before it entered the bottle and from one side of this tee copper tubing was run to a source of air. Air originally under 173 psi pressure was first reduced by a pressure

1. Introduction

2. Methodology

The first part of the study is a literature review.

The second part of the study is a data collection.

The third part of the study is a data analysis.

The fourth part of the study is a conclusion.

The fifth part of the study is a discussion.

The sixth part of the study is a reference.

The seventh part of the study is an appendix.

The eighth part of the study is a glossary.

The ninth part of the study is a list of figures.

The tenth part of the study is a list of tables.

The eleventh part of the study is a list of abbreviations.

The twelfth part of the study is a list of symbols.

The thirteenth part of the study is a list of units.

The fourteenth part of the study is a list of definitions.

The fifteenth part of the study is a list of acronyms.

The sixteenth part of the study is a list of initialisms.

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The eighteenth part of the study is a list of units.

The nineteenth part of the study is a list of definitions.

The twentieth part of the study is a list of acronyms.

regulator to 65 psi. It was further reduced and regulated by a Ballistic Pressure Regulator which allowed a fine accurate control of the pressure over a range of 2 psi to 30 psi.

From the other side of the tap a lead was run to a mercury manometer. This measured the pressure existing at the end of the copper tubing in the bottle. Therefore, differences in fluid level in the bottle at various times during the run would not affect the pressure placed on the system and a constant pressure could be maintained.

Since the level of the outlet of the copper tube in the bottle was adjusted to the same level as that of the inlet to the core, with a fluid connection to this inlet, the pressure at the inlet was the same as that measured at the end of the tube in the bottle.

Figure II shows the flow system used in this experiment. The components of this system are:

- (A) High pressure regulator and reducer
- (B) Low pressure regulator and reducer
- (C) Mercury manometers
- (D) Pyrex bottle fluid reservoir
- (E) Valve for purging fluid system
- (F) Synthetic core
- (G) Valve and spigot at outlet
- (H) Manometer connections
- (I) Graduate
- (J) Screen type filter





For the runs made in the vertical position essentially the same set up was maintained and a correction was made for the difference in height of the inlet to the tube and the point where the pressure was measured in the bottle.

From Figure II it can be seen that the flow system consists only of applying air pressure to the bottle (b) which causes the fluid in the bottle to flow through the filler to the inlet of the tube, then passing through the tube to the outlet where it is caught and measured in the 100 cubic centimeter graduate (I).

The apparatus used to measure the per cent of sugar in the efflux stream was a Spencer Abbe-type Refractometer. This refractometer is accurate to the third decimal place. From the knowledge of the amount of sugar in the efflux stream the per cent of original fluid could be calculated.

1. The first part of the report deals with the general situation of the country.

2. The second part deals with the economic situation of the country.

3. The third part deals with the social situation of the country.

4. The fourth part deals with the cultural situation of the country.

5. The fifth part deals with the political situation of the country.

6. The sixth part deals with the international situation of the country.

7. The seventh part deals with the future of the country.

8. The eighth part deals with the conclusion of the report.

9. The ninth part deals with the appendix of the report.

10. The tenth part deals with the bibliography of the report.

11. The eleventh part deals with the index of the report.

12. The twelfth part deals with the list of figures of the report.

13. The thirteenth part deals with the list of tables of the report.

14. The fourteenth part deals with the list of maps of the report.

15. The fifteenth part deals with the list of abbreviations of the report.

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17. The seventeenth part deals with the list of units of the report.

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28. The twenty-eighth part deals with the list of acronyms of the report.

29. The twenty-ninth part deals with the list of initialisms of the report.

30. The thirtieth part deals with the list of abbreviations of the report.

## CHAPTER VI

### EXPERIMENTAL PROCEDURE

After completing the partial consolidation and drying of the core, a series of permeability tests were run with air. On the completion of the permeability tests porosity was obtained by two different methods. When the permeability and porosity were deemed satisfactory the core was saturated with water and connected to a fluid system that was under a controlled pressure. Then the water in the core could be displaced by another fluid which in turn could be displaced by another fluid. During these displacements, rate and composition of the effluent stream were measured.

#### Permeability Determinations

Upon running initial permeability test it was found that one end section of the core had a very low permeability compared to the other two sections. Upon removing the end plate it could be seen that a small hard plug had been formed in the center of the core. This plug appeared to extend into the core for only a few centimeters. Using a diamond saw approximately 6 centimeters was cut from the end of the core which was then squared by the use of fine emery cloth. This

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resulted in a core 33.7 centimeters in length. When permeabilities were run on this core it was found to have an overall permeability of 3.97 darcies while the three sections had permeabilities of 3.31, 4.01, and 3.60 darcies. All of these permeabilities were determined in the usual manner using air, after the values were determined they were plotted against the reciprocal of the mean pressure at which they were obtained and extrapolated to an infinite pressure to correct for the Klinkenberg effect.

### Porosity Determinations

Two methods were used to determine the porosity of the core. The first method was to build up a pressure in the core, record this pressure, then lower the pressure by metering out a known volume of air and again record the pressure. Applying the perfect gas law the volume of space the gas occupied in the core could be calculated. The total volume of the tube and fittings can be determined from their dimensions, thus the porosity determined. The average value found by this method was .337.

The second method used the difference in dry and wet weights of the core and was described in a previous section. The porosity by this method was found to be .337. This method was thought to be more accurate than the one using air, so it was used in all calculations.

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### Index of Refraction Measurements

The solutions used in this experiment were transparent, thus making the proper instrument the index of refraction could easily be measured. Since the per cent of sucrose in an aqueous solution is directly related to its index of refraction a measurement of this value could be converted easily to per cent of sucrose present.

In this work the index of refraction of both the original fluid in the core and of the displacing fluid were measured before a run was started. At regular intervals during the run index of refraction of the efflux was measured and with these values the per cent of the original fluid in the efflux could be calculated.

### Experimental Run

After the permeability and porosity determinations had been made on the core it was left saturated with distilled water which was displaced by an aqueous sucrose solution of known index of refraction. The pressure bottle was filled with distilled water, then connected to the air system and to the core by means of plastic tubing. (See Figure II.)

Next a pressure was applied to the system through the regulator which maintained this pressure constant. A valve at the efflux end of the core was opened allowing the original fluid in the core to be displaced by the sucrose solution. The volume of the displaced fluid and the rate of flow





of the effluent stream was measured and recorded at the same time the index of refraction of the effluent was obtained.

By referring to the tables in the Handbook of Chemistry and Physics [14], the per cent of sucrose by weight in the effluent was obtained. The temperature was measured and a correction applied to the above percentage. From another table in the Handbook the amount of sucrose (grams per liter) was obtained. Since the same values were obtained for the original sucrose solution the amount of the original fluid present in the effluent could be calculated. These measurements and calculations were made at regular intervals during the displacement process.

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## EXPERIMENTAL DATA





## TABLE I

SUGAR SOLUTION

Temperature, 37° C

P = 220 mm.Hg.

Original Fluid (Distilled  
water)Displacing Fluid (Sugar  
Solution) $n_D = 1.3383$  $n_D = 1.3710$ 

Viscosity = .0546 cp

Viscosity = 1.96 cp

% sugar = 24.72%

cu. cms.	$n_D$	West. tube Volume	% Sugar in off.	wt. of sugar in off.	wt. of Dis- placing fluid in off.	% of fluid in off.
100	1.3383					
200	1.3331	.992	1.4	14	6.17	94.8
300	1.3281	1.99	13.8	139	31.5	48.6
400	1.3230	1.99	21.0	235	37.5	13.8
500	1.3180	1.99	23.30	255	44	6.0
1000	1.3099	1.121	23.8	262	45.7	2.3
1050	1.3700	1.125	24.30	267	46.2	1.8
1100	1.3700	1.127	24.40	268	47.2	1.0
1200	1.3710	1.432	24.75	271	100	0

 $n_D$  = Index of refraction.

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# Table II

WATER-SUGAR SYSTEM

Temperature = 25° C

P = 220 mm. Hg.

Original Fluid (Sugar Solution)

Displacing Fluid (Distilled Water)

$n = 1.3710$

$n = 1.3335$

Viscosity = 2.35 cp .

Viscosity = .0037 cp .

% Sugar = 24.72%

cu. cms. measured	$n =$ refractive	transl. loss volume	% sugar in eff.	cu. cm. sugar in eff.	% of fluid in eff.
500	1.3710	.552	24.72	270	1.00
600	1.3708	.662	24.46	268	.992
680	1.3690	.718	23.40	236	.950
700	1.3640	.773	20.40	220.5	.816
800	1.3648	.823	14.57	154	.61
880	1.3621	.938	13.02	137	.507
950	1.3475	1.048	10.02	104	.398
1000	1.3449	1.108	8.37	85.5	.317
1100	1.3418	1.218	6.32	64.5	.239
1200	1.3402	1.325	5.25	56	.207
1400	1.3361	1.548	2.40	25	.093
1600	1.3336	1.770	.48	6.5	.024
1700	1.3327	1.878	0	0	0
1800	1.3326				

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TABLE III  
REFRACTIVE INDEX

Temperature = 25° C

λ = 589 mμ. Cd.

Original Fluid (Sugar  
Solution)Displacing Fluid (Distilled  
water)

n = 1.4088

n = 1.3335

Viscosity = 3.1 cp

Viscosity = .0037 cp

% Sugar = 45.03%

Wt. of Sample	n	Wt. of Pure Volume	% Sugar in eff.	Wt. of sugar in eff.	% ori- ginal fluid in eff.
0	1.4088				
200	1.4088	.821	45.03	341	1.00
400	1.4088	.464	45.91	338	.954
500	1.3992	.382	38.36	400	.754
550	1.3767		29.56	332	.614
600	1.3664	.662	21.34	236	.456
650	1.3564		16.09	181	.334
700	1.34	.773	11.12	116	.214
750	1.3472		9.87	102	.188
800	1.3151	.983	12.32	130	.240
850	1.3468	.982	9.42	98	.181
1000	1.3472	1.102	9.87	102	.188
1085	1.3485	1.197	10.72	111	.205
1350	1.3472	1.480	9.87	102	.188
1725	1.3429	1.905	7.02	72	.133
1875	1.3412				
2000	1.3387	2.210	4.2	43	.0784
2600	1.3353	2.870	1.9	19	.035
3300	1.3349	3.640			
3725	1.3351	4.145			



TABLE IV  
NEW METHOD 4

Temperature = 27° C  
Original Fluid (Sugar  
Solution)  
 $n = 1.3910$   
Viscosity = 3.8 cp  
Sugar = 39.21%

$P = 230$  mm. Hg.  
Displacing Fluid (Distilled  
Water)  
 $n = 1.3335$   
Viscosity = .9937 cp

Fl. cm.	$n =$	Rate cm/min.	Fract. Pure Volume	Sugar in eff.	wt. of sugar in eff.	Dist- illed fluid in efflux
0	1.3910	3.8				
100	1.3910	4.9	.11			
200	1.3910	5.7	.221			
300	1.3910	6.2	.331			
400	1.3910	6.3	.444			
500	1.3910	7.2	.552	36.61	413	1.00
600	1.3788	7.3	.662	38.81	384	.783
750	1.3753	8	.717	37.51	303	.734
900	1.3635	8.6	.863	33.00	217	.533
950	1.3584	8.5	.883	13.23	138	.334
1000	1.3480		1.000	10.37	113.5	.274
1050	1.3469	8.7	1.133	8.62	78	.233
1060	1.3457		1.163	8.27	61.3	.221
1150	1.3441	10	1.332	7.61	50	.183
1200	1.339	10.3	1.353	3.7	37	.0886
1300	1.339	10.3	1.438	3.7	37	.0886
1500	1.3371	10.6	1.635	3.1	31	.073
1600	1.3360	10.3	1.770	3.7	37	.0886
1700	1.3360	10.6	1.878	2.4	24	.0571
1800	1.3332	11.1	1.950	2.3	23	.0537
2000	1.3323	12.5	2.23	2.00	20	.0428
2200	1.3332	13.8	2.54	.43	43	.021





TABLE I  
 RHEO VISCOSITY 2

Temperature = 26° C  
 Original Fluid (sugar  
 solution)  
 $n = 1.3721$   
 Viscosity = 1.00 cp  
 $\eta$  sugar = 14.925

P = 760 mm. Hg.  
 Displacing Fluid (distilled  
 water)  
 $n = 1.3324$   
 Viscosity = .0107 cp

Revol. Per Second	$n$	Rate cc/min.	Revol. Per Minute	Water in eff.	Water in eff.	Water in eff.
Produced	efflux					
100	1.3713	37				
200	1.3711	42				
300	1.3710	45	.002	24.71	273.2	100
400	1.3700		.040	24.13	265	97.3
500	1.3690		.072	22.83	250.3	92.0
710	1.3621	33	.704	16.05	212	78.3
800	1.3610		.983	12.90	155.5	49.7
950	1.3488	61	.832	10.69	114.3	42.0
900	1.3485	62	.893	8.80	82.2	30.1
850	1.3482	62	1.042	8.80	82	32.3
1000	1.3456	51	1.135	8.80	72	28.7
1050	1.3454	51	1.153	8.8	71	28.4
1100	1.3435	51	1.21	7.5	77	29.3
1120	1.3430	50	1.27	7.15	73	27.9
1200	1.3413	51	1.353	5.96	61	22.4
1300	1.3394	53	1.433	4.70	49	18.0
1400	1.3377	54	1.545	3.82	36	12.2
1500	1.3344	53	1.632	1.84	13	4.9
1600	1.3328	55	1.770			
1700	1.3323	55	1.975			
1800	1.3320	54	1.850			

# TABLE 1

Summary of the results of the analysis of the data obtained from the experiments conducted during the period from January 1, 1960, to December 31, 1961, at the U.S. Army Research Office, Durham, North Carolina.

Experiment	Sample Size	Mean	Standard Deviation	Standard Error	Confidence Interval	Significance Level
1	100	1.250	0.100	0.032	1.186, 1.314	0.05
2	100	1.250	0.100	0.032	1.186, 1.314	0.05
3	100	1.250	0.100	0.032	1.186, 1.314	0.05
4	100	1.250	0.100	0.032	1.186, 1.314	0.05
5	100	1.250	0.100	0.032	1.186, 1.314	0.05
6	100	1.250	0.100	0.032	1.186, 1.314	0.05
7	100	1.250	0.100	0.032	1.186, 1.314	0.05
8	100	1.250	0.100	0.032	1.186, 1.314	0.05
9	100	1.250	0.100	0.032	1.186, 1.314	0.05
10	100	1.250	0.100	0.032	1.186, 1.314	0.05
11	100	1.250	0.100	0.032	1.186, 1.314	0.05
12	100	1.250	0.100	0.032	1.186, 1.314	0.05
13	100	1.250	0.100	0.032	1.186, 1.314	0.05
14	100	1.250	0.100	0.032	1.186, 1.314	0.05
15	100	1.250	0.100	0.032	1.186, 1.314	0.05
16	100	1.250	0.100	0.032	1.186, 1.314	0.05
17	100	1.250	0.100	0.032	1.186, 1.314	0.05
18	100	1.250	0.100	0.032	1.186, 1.314	0.05
19	100	1.250	0.100	0.032	1.186, 1.314	0.05
20	100	1.250	0.100	0.032	1.186, 1.314	0.05
21	100	1.250	0.100	0.032	1.186, 1.314	0.05
22	100	1.250	0.100	0.032	1.186, 1.314	0.05
23	100	1.250	0.100	0.032	1.186, 1.314	0.05
24	100	1.250	0.100	0.032	1.186, 1.314	0.05
25	100	1.250	0.100	0.032	1.186, 1.314	0.05
26	100	1.250	0.100	0.032	1.186, 1.314	0.05
27	100	1.250	0.100	0.032	1.186, 1.314	0.05
28	100	1.250	0.100	0.032	1.186, 1.314	0.05
29	100	1.250	0.100	0.032	1.186, 1.314	0.05
30	100	1.250	0.100	0.032	1.186, 1.314	0.05

## TABLE VI

WATER COLUMN C  
(Vertical Run - Upward)

Temperature = 20° C

P = 380 mm. Hg.

Original Fluid (distilled water)

Displacing Fluid (Sugar Solution)

n = 1.3324

n = 1.3903

Viscosity = .0737 cp

Viscosity = 3.7 cp

% Sugar = 35.81%

Time, sec.	n =	Rate cm./min.	Fract. Wave Volume	% Sugar in eff.	% Sugar in eff. g./liter	% Sugar in eff. g./liter
0		12				
135	1.3324	9.5	.138			
200		9.5	.281			
325		7	.389			
455	1.3324	6.7	.470			
500		5.1	.552			
600		4.6	.663			
700		4.2	.771			
825	1.3324	4	.822			
860	1.3324		.938			
900	1.3330	3.7	.993	.53	4	100
915	1.3400		1.003	1.23	53	99
950	1.3408		1.014	2.71	102.5	97.3
950	1.3508		1.015	12.22	202	72.3
945	1.3511		1.045	35.80	344.5	51.6
955	1.3508		1.058	33.85	363	17
960	1.3500		1.064	34.85	400.6	7.7
965	1.3500		1.066	35.15	404	3.6
1000	1.3500	3.2	1.103	35.40	428	2.6
1025	1.3505					1.6
1050	1.3500					
1100	1.3503	3.2	1.21	35.85	415	





TABLE VII

Run Number 7  
(Vertical Run - Down)

Temperature = 26° C

P = 220 mm. Hg.

Original Fluid (Sugar  
solution)Displacing Fluid (Distilled  
water)

n = 1.3302

n = 1.3334

Viscosity = 3.7 cp

Viscosity = .3737 cp

Sugar = 33.21%

Run, cm.	n =	Rate	Fract. Frac. Volume	% Sugar in eff.	wt. of sugar in eff.	% Ori- ginal fluid in eff.
50	1.3308	3.6	.0551			
100	1.3308	4.2	.11			
200	1.3308	4.5	.221			
300	1.3308	4.5	.331			
400	1.3308	4.7	.442			
500	1.3308	4.5	.622	32.39	415	100
550	1.3343		.612	32.33	368	88.6
570	1.3799		.629	29.78	353.5	80.8
600	1.3767	5.7	.632	27.73	311.5	73.0
650	1.3704		.722	24.31	257.0	64.0
700	1.3654	6.4	.773	21.36	232	55.9
750	1.3590		.832	18.97	160	43.4
800	1.3500	6.7	.853	15.01	103	40.3
850	1.3408		.959	13.14	104	40.0
900	1.3390	7.0	.963	12.79	170	43.2
950	1.3350		1.0326	12.82	165	50.0
1000	1.3322	7.0	1.106	12.14	122	33.0
1050	1.3499		1.165	11.89	122.5	39.3
1100	1.3483	7.8	1.216	10.89	111.0	37.7
1150	1.3499		1.215	9.69	100.5	24.1
1200	1.3483	7.8	1.270	8.14	64.8	22.3
1300	1.3437	9	1.325	7.68	79	19.0
1400	1.3411		1.435	5.86	59	14.2
1500	1.3387	8.5	1.545	4.56	44	10.6
1600	1.3370		1.655	3.23	32.5	7.8
1700	1.3343	7.5	1.770	1.43	15	3.8
1800	1.3330		1.900	.4	4	.41
2000	1.3323	10.4	2.1	.4	4	.91
2060	1.3321	10.4	2.210			

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TABLE VIII

RUN NUMBER 8  
(Vertical Run - Upward)

Temperature = 27° C

P = 220 mm. Hg.

Original Fluid (Distilled  
Water)

Displacing Fluid (Sugar  
Solution)

$n = 1.3343$

$n = 1.3703$

Viscosity = .0045 cp

Viscosity = 1.75 cp

% Sugar = 24.72%

Dist. mm. Travelled	$n$ at film	Rate cm/min.	Transl. Time sec.
0		13	
100	1.3343	13.0	.11
200		8.0	.201
300		8.0	.302
400		8	.445
500		7.1	.612
700		5.8	.775
800		5.0	.905
900	1.3343	4.3	.983
950	1.3413		1.03
980	1.3500	4.0	1.00
990	1.3609		
1000			
1050	1.3703	4.8	1.13
1080	1.3700		





TABLE IX

RUN NUMBER 2

Temperature = 27° C

P = 250 mm. Hg.

Original Fluid (Sugar  
Solution)Displacing Fluid (Distilled  
Water)

n = 1.3709

n = 1.3333

Viscosity = 1.42 cp

Viscosity = .3443 cp

Sugar = 24.5%

Time, sec.	n =	Flow, cc/min.	Transp. Pore Volume	Time, sec.	Flow, cc/min.	Transp. Pore Volume
Produced	efflux			in eff.		in eff.
						Displ. fluid in eff.
100	1.3709	4.3				
250	1.3709	4.5				
350	1.3709	4.6				
500	1.3709	4.6				
550	1.3709	4.8				
600	1.3708	5.0	.663			
810	1.3708	5.0	.873	24.60	571.5	100
925	1.3695	5.0	.980	23.83	562	96
950	1.3679	5.1	.717	22.88	550.8	92
700	1.3664	5.2	.773	21.43	523	82.5
730	1.3656	5.3	.827	19.48	511	73.9
800	1.3577	5.2	.833	18.73	170	63.4
880	1.3543		.939	14.91	158	58.0
900	1.3507	5.4	.963	12.20	129	47.0
930	1.3489		1.043	11.10	116	43.0
1000	1.3486	5.6	1.135	8.61	93	38.3
1050	1.3437		1.160	7.73	73.3	28.9
1150	1.3393	5.7	1.233	4.43	44	18.1
1200	1.3392	5.7	1.235	3.73	37.4	13.7
1650	1.3326	5.8	1.320			
1700	1.3328		1.375			

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## TABLE 1

AND FIGURE 10

Temperature = 22° C

P = 280 mm. Hg.

Original fluid (distilled  
water)Hypodermic fluid (sugar  
solution) $n = 1.3324$  $n = 1.3365$ 

Viscosity = .8737 cp

Viscosity = 1.0 cp

Sugar = 4.1%

mm. Hg.	$n$	mm. Hg.	Part. Vol.
Original	affine	affine	
100	1.3324	13	.11
200	1.3324	13	.221
300	1.3324	12	.331
400	1.3324	11	.442
500	1.3324	10.3	.552
600	1.3324	10	.662
700	1.3324	9.8	.773
800	1.3324	9.5	.883
850	1.3324	9.3	.933
900	1.3370	8.9	.993
960	1.3372		1.060
1000	1.3378	7.9	1.105
1100	1.3382		1.21
1400	1.3385		1.545

TABLE I  
OF THE  
SOLUBILITY OF  
SALT

at 100° C.

in water

SALT		SOLUBILITY	
Name		Grams per 100 grams of water	
Sodium chloride		35.7	
Sodium sulfate		4.7	
Sodium carbonate		32.9	
Sodium bicarbonate		9.6	
Sodium nitrate		12.5	
Sodium acetate		51.3	
Sodium formate		64.5	
Sodium oxalate		0.67	
Sodium malonate		1.0	
Sodium succinate		1.5	
Sodium fumarate		0.03	
Sodium maleate		0.001	
Sodium phthalate		0.0001	
Sodium terephthalate		0.0001	
Sodium pyruvate		1.0	
Sodium lactate		17.0	
Sodium citrate		13.0	
Sodium tartrate		12.5	
Sodium bitartrate		1.0	
Sodium malate		1.0	
Sodium ascorbate		0.001	
Sodium glutamate		10.0	
Sodium proline		0.001	
Sodium glycine		1.0	
Sodium alanine		1.0	
Sodium valine		1.0	
Sodium leucine		1.0	
Sodium isoleucine		1.0	
Sodium threonine		1.0	
Sodium serine		1.0	
Sodium methionine		1.0	
Sodium cysteine		1.0	
Sodium proline		0.001	
Sodium hydroxyproline		0.001	
Sodium hydroxylysine		0.001	
Sodium lysine		1.0	
Sodium arginine		1.0	
Sodium histidine		1.0	
Sodium aspartate		1.0	
Sodium glutamate		1.0	
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Flow rate, gpm.	Flow rate, cc/min.	Flow rate, cc/min.	Flow rate, cc/min.	Flow rate, cc/min.	Flow rate, cc/min.	Flow rate, cc/min.
400	1.3385	10.7				
700	1.3385					
900	1.3385	10.7	.883	4.16	42	1.00
850	1.3385		.838	4.16	42	1.00
880	1.3343	10.7	.972	2.66	28	.67
900	1.3342		.963	1.26	13	.31
925	1.3340		1.02	1.06	11	.26
975	1.3335		1.075	.71	7	.17
1000	1.3330	10.7	1.103	.56	3.6	.086
1050	1.3326		1.160			
1100	1.3324	10.7	1.220			



TABLE XII  
COMPOSITE DATA

Viscosity Ratio Maximal Fluid Original Fluid	Pore Volume Produced at Complete Recovery	Per cent of Orig. Fluid Recovered at this Pore Volume	Index of Refraction of Total Displaced Liquid
.110	4.1	72.7	1.3300
.230	3.0	85.3	1.3326
.400	1.57	83.7	
.678	1.26	93.7	1.3301
4.23	1.3	88.0	

# TABLE I

continued

TABLE I (continued)

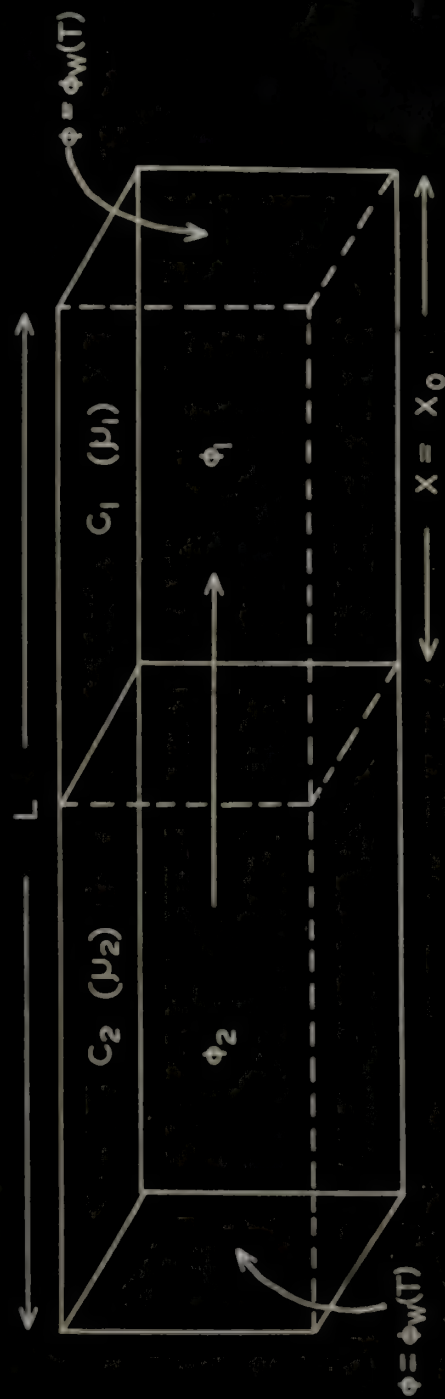
Run No.	Time (min)	Temp. (°C)	Pressure (mm Hg)	Flow Rate (ml/min)	Conc. (g/ml)
1	10.0	100.0	1.0	1.0	1.0
2	10.0	100.0	1.0	1.0	1.0
3	10.0	100.0	1.0	1.0	1.0
4	10.0	100.0	1.0	1.0	1.0
5	10.0	100.0	1.0	1.0	1.0
6	10.0	100.0	1.0	1.0	1.0
7	10.0	100.0	1.0	1.0	1.0
8	10.0	100.0	1.0	1.0	1.0
9	10.0	100.0	1.0	1.0	1.0
10	10.0	100.0	1.0	1.0	1.0
11	10.0	100.0	1.0	1.0	1.0
12	10.0	100.0	1.0	1.0	1.0
13	10.0	100.0	1.0	1.0	1.0
14	10.0	100.0	1.0	1.0	1.0
15	10.0	100.0	1.0	1.0	1.0
16	10.0	100.0	1.0	1.0	1.0
17	10.0	100.0	1.0	1.0	1.0
18	10.0	100.0	1.0	1.0	1.0
19	10.0	100.0	1.0	1.0	1.0
20	10.0	100.0	1.0	1.0	1.0
21	10.0	100.0	1.0	1.0	1.0
22	10.0	100.0	1.0	1.0	1.0
23	10.0	100.0	1.0	1.0	1.0
24	10.0	100.0	1.0	1.0	1.0
25	10.0	100.0	1.0	1.0	1.0
26	10.0	100.0	1.0	1.0	1.0
27	10.0	100.0	1.0	1.0	1.0
28	10.0	100.0	1.0	1.0	1.0
29	10.0	100.0	1.0	1.0	1.0
30	10.0	100.0	1.0	1.0	1.0
31	10.0	100.0	1.0	1.0	1.0
32	10.0	100.0	1.0	1.0	1.0
33	10.0	100.0	1.0	1.0	1.0
34	10.0	100.0	1.0	1.0	1.0
35	10.0	100.0	1.0	1.0	1.0
36	10.0	100.0	1.0	1.0	1.0
37	10.0	100.0	1.0	1.0	1.0
38	10.0	100.0	1.0	1.0	1.0
39	10.0	100.0	1.0	1.0	1.0
40	10.0	100.0	1.0	1.0	1.0
41	10.0	100.0	1.0	1.0	1.0
42	10.0	100.0	1.0	1.0	1.0
43	10.0	100.0	1.0	1.0	1.0
44	10.0	100.0	1.0	1.0	1.0
45	10.0	100.0	1.0	1.0	1.0
46	10.0	100.0	1.0	1.0	1.0
47	10.0	100.0	1.0	1.0	1.0
48	10.0	100.0	1.0	1.0	1.0
49	10.0	100.0	1.0	1.0	1.0
50	10.0	100.0	1.0	1.0	1.0
51	10.0	100.0	1.0	1.0	1.0
52	10.0	100.0	1.0	1.0	1.0
53	10.0	100.0	1.0	1.0	1.0
54	10.0	100.0	1.0	1.0	1.0
55	10.0	100.0	1.0	1.0	1.0
56	10.0	100.0	1.0	1.0	1.0
57	10.0	100.0	1.0	1.0	1.0
58	10.0	100.0	1.0	1.0	1.0
59	10.0	100.0	1.0	1.0	1.0
60	10.0	100.0	1.0	1.0	1.0
61	10.0	100.0	1.0	1.0	1.0
62	10.0	100.0	1.0	1.0	1.0
63	10.0	100.0	1.0	1.0	1.0
64	10.0	100.0	1.0	1.0	1.0
65	10.0	100.0	1.0	1.0	1.0
66	10.0	100.0	1.0	1.0	1.0
67	10.0	100.0	1.0	1.0	1.0
68	10.0	100.0	1.0	1.0	1.0
69	10.0	100.0	1.0	1.0	1.0
70	10.0	100.0	1.0	1.0	1.0
71	10.0	100.0	1.0	1.0	1.0
72	10.0	100.0	1.0	1.0	1.0
73	10.0	100.0	1.0	1.0	1.0
74	10.0	100.0	1.0	1.0	1.0
75	10.0	100.0	1.0	1.0	1.0
76	10.0	100.0	1.0	1.0	1.0
77	10.0	100.0	1.0	1.0	1.0
78	10.0	100.0	1.0	1.0	1.0
79	10.0	100.0	1.0	1.0	1.0
80	10.0	100.0	1.0	1.0	1.0
81	10.0	100.0	1.0	1.0	1.0
82	10.0	100.0	1.0	1.0	1.0
83	10.0	100.0	1.0	1.0	1.0
84	10.0	100.0	1.0	1.0	1.0
85	10.0	100.0	1.0	1.0	1.0
86	10.0	100.0	1.0	1.0	1.0
87	10.0	100.0	1.0	1.0	1.0
88	10.0	100.0	1.0	1.0	1.0
89	10.0	100.0	1.0	1.0	1.0
90	10.0	100.0	1.0	1.0	1.0
91	10.0	100.0	1.0	1.0	1.0
92	10.0	100.0	1.0	1.0	1.0
93	10.0	100.0	1.0	1.0	1.0
94	10.0	100.0	1.0	1.0	1.0
95	10.0	100.0	1.0	1.0	1.0
96	10.0	100.0	1.0	1.0	1.0
97	10.0	100.0	1.0	1.0	1.0
98	10.0	100.0	1.0	1.0	1.0
99	10.0	100.0	1.0	1.0	1.0
100	10.0	100.0	1.0	1.0	1.0



71-1111



FIGURE I

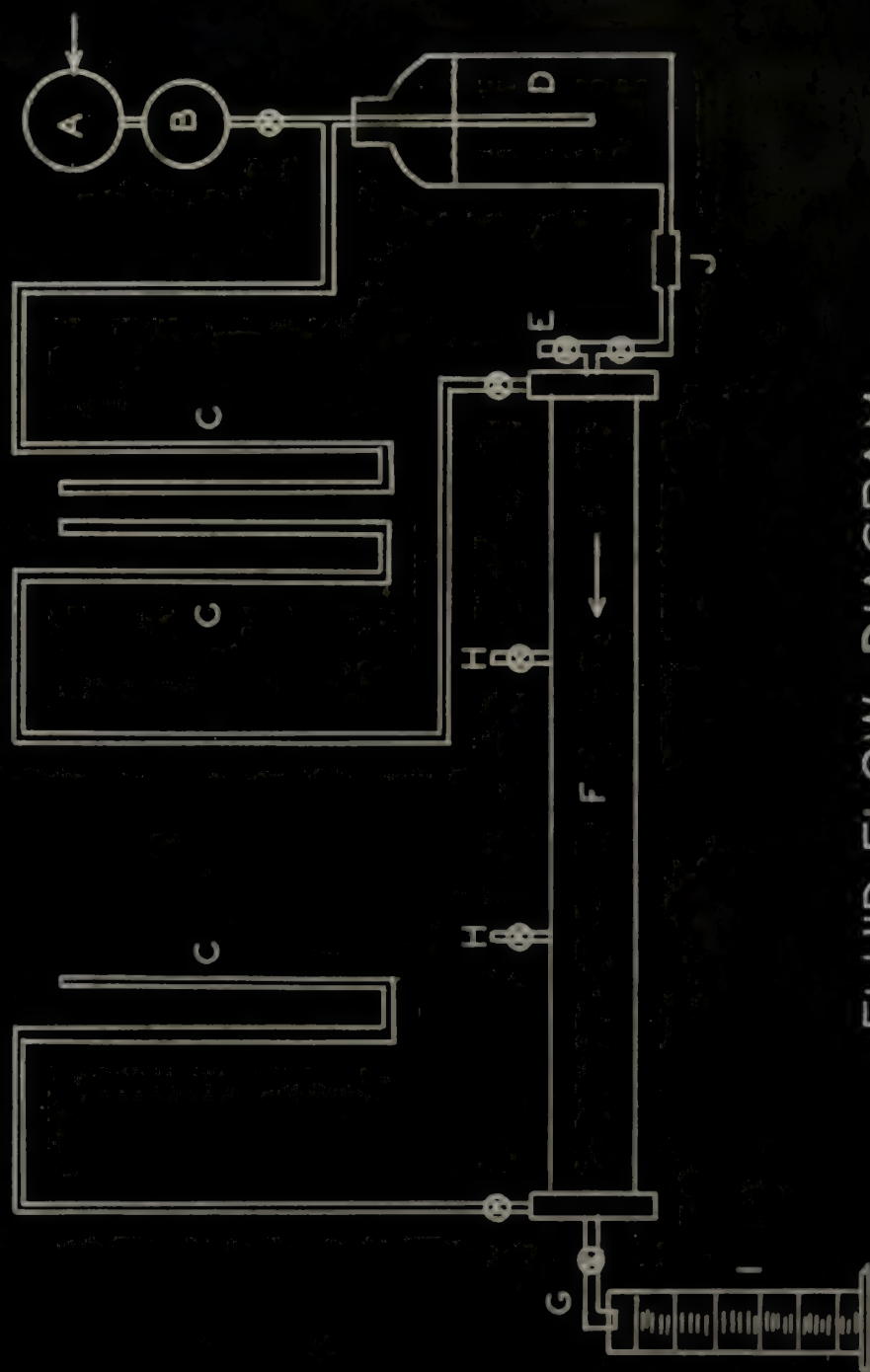


A LINEAR ENCROACHMENT SYSTEM  
AFTER MUSKAT



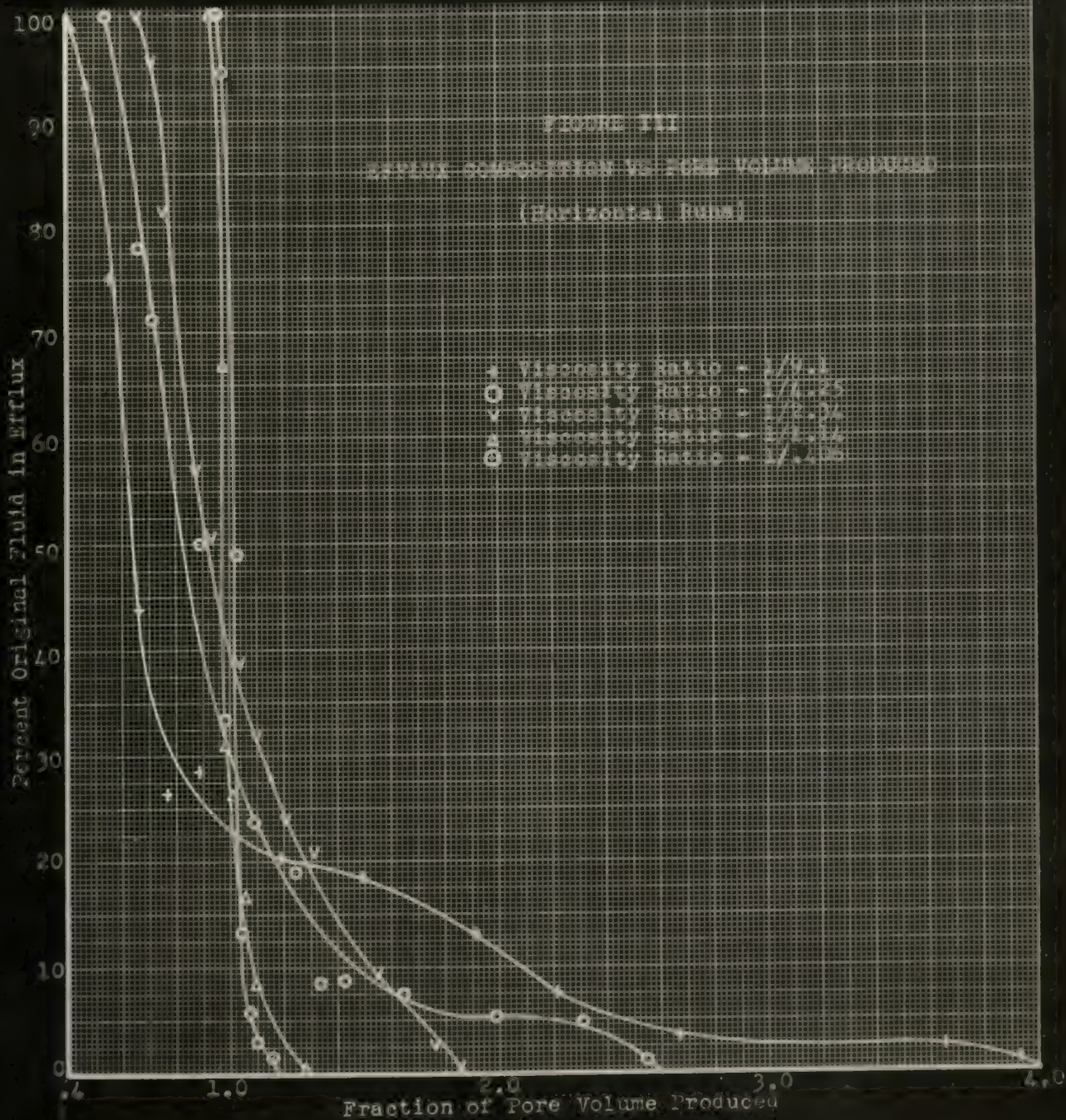


FIGURE II



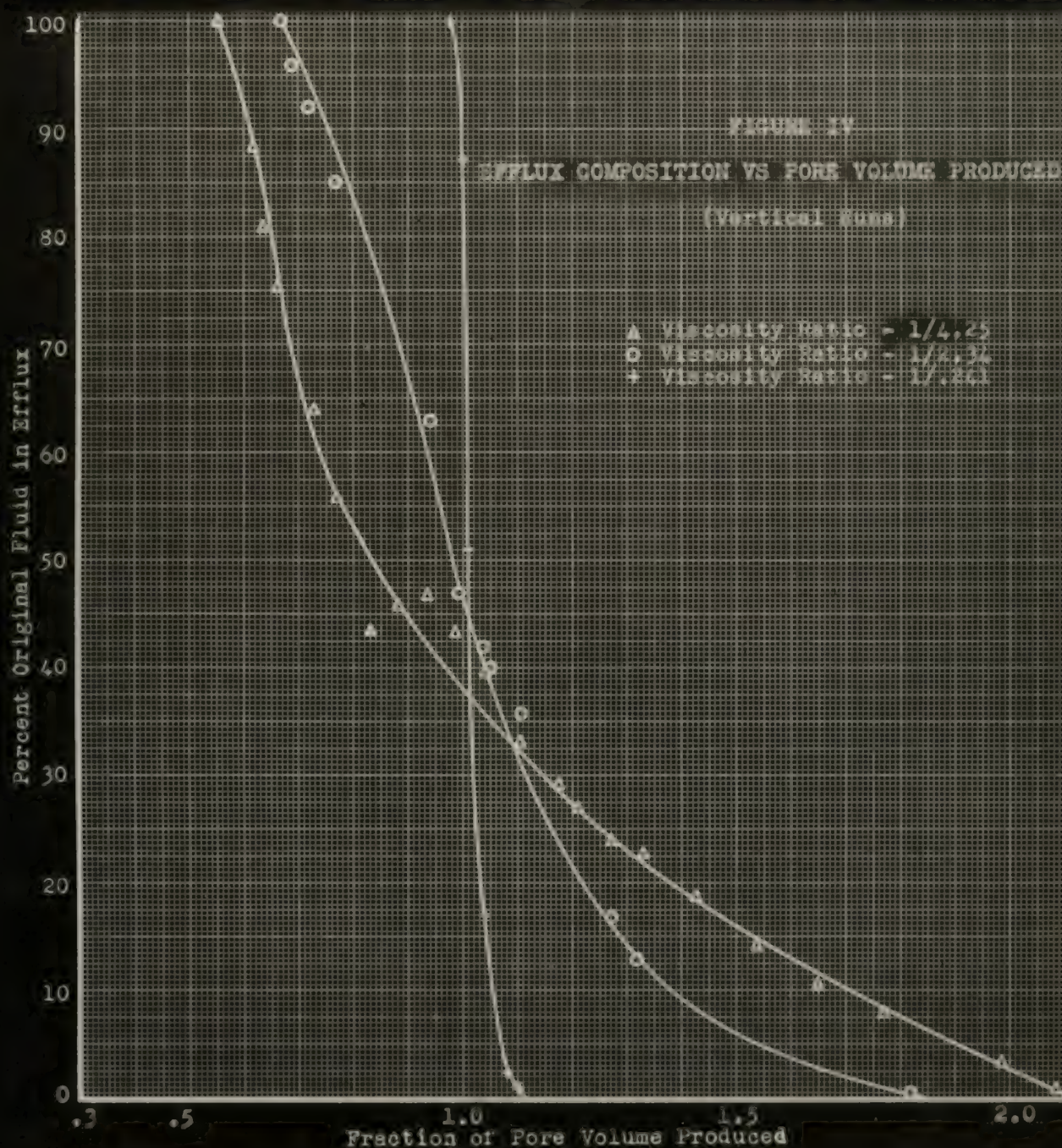
FLUID FLOW DIAGRAM





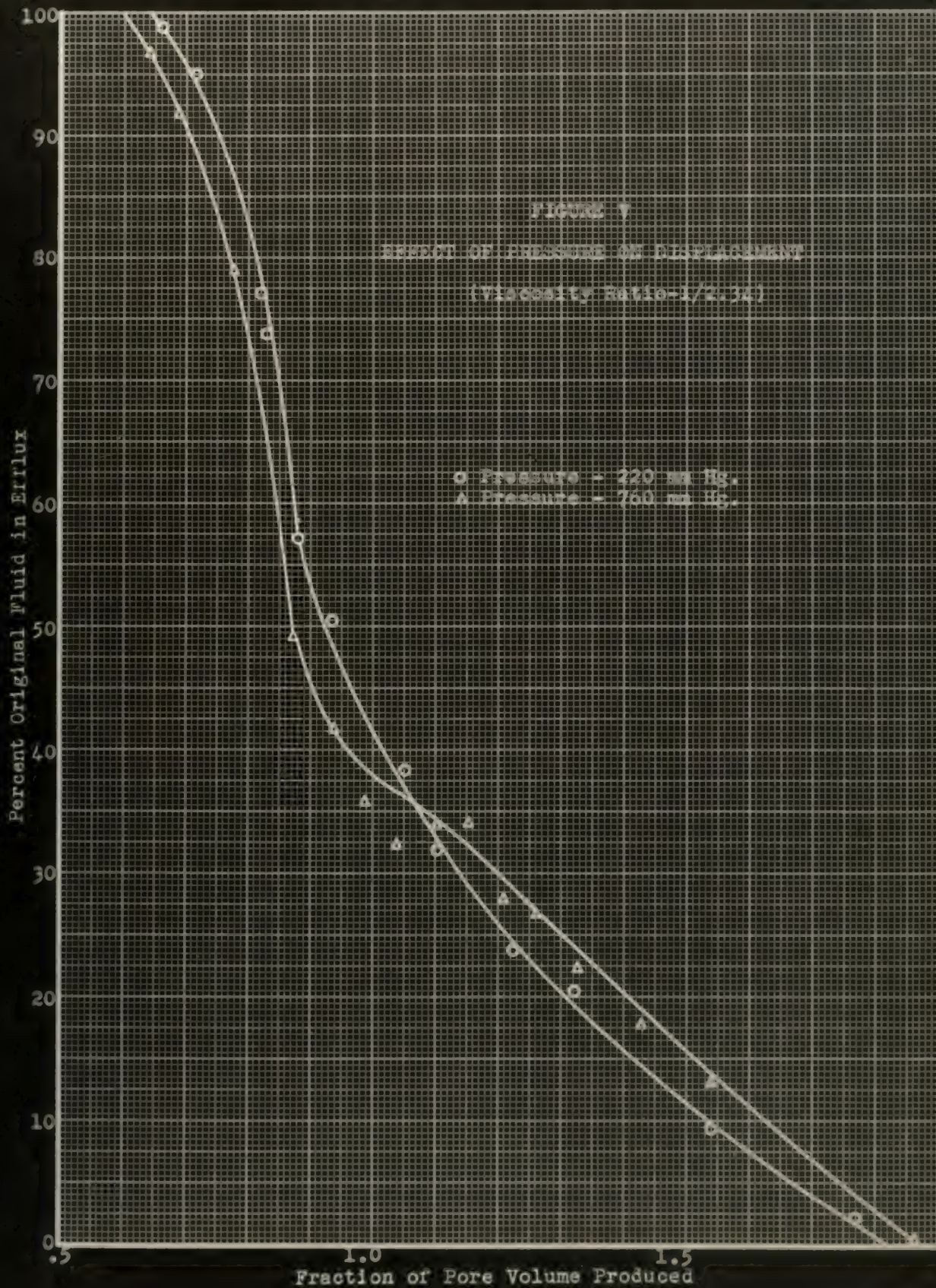






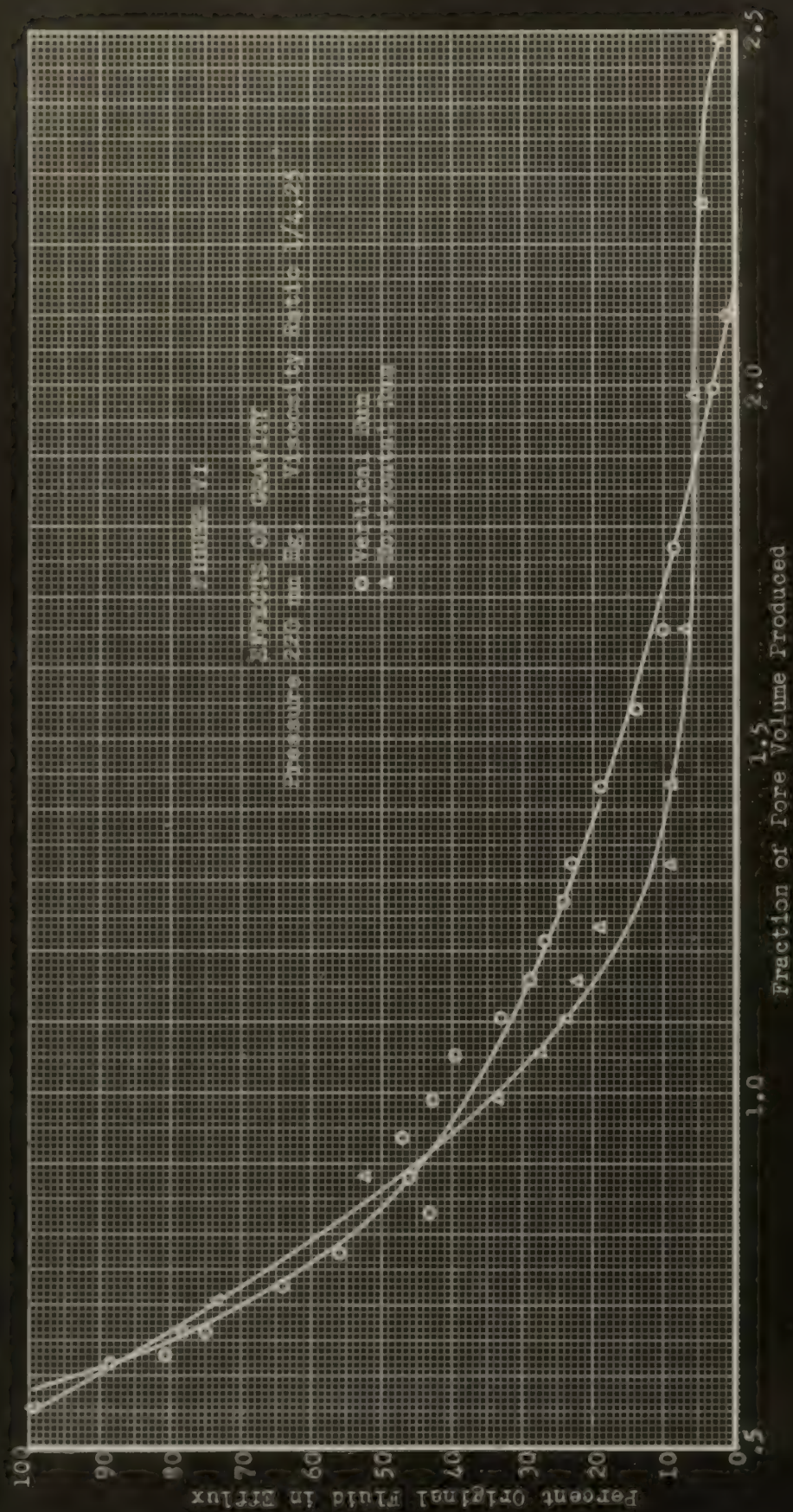
















11

FIGURE 7-11

RATE VS. PORE VOLUME PRODUCED

10

9

8

7

Rate - cc/min.

6

5

4

3

2

1

0

○ Viscosity Ratio 1/4.25  
▲ Viscosity Ratio 1/4.25

Fraction of Pore Volume Produced

1.5

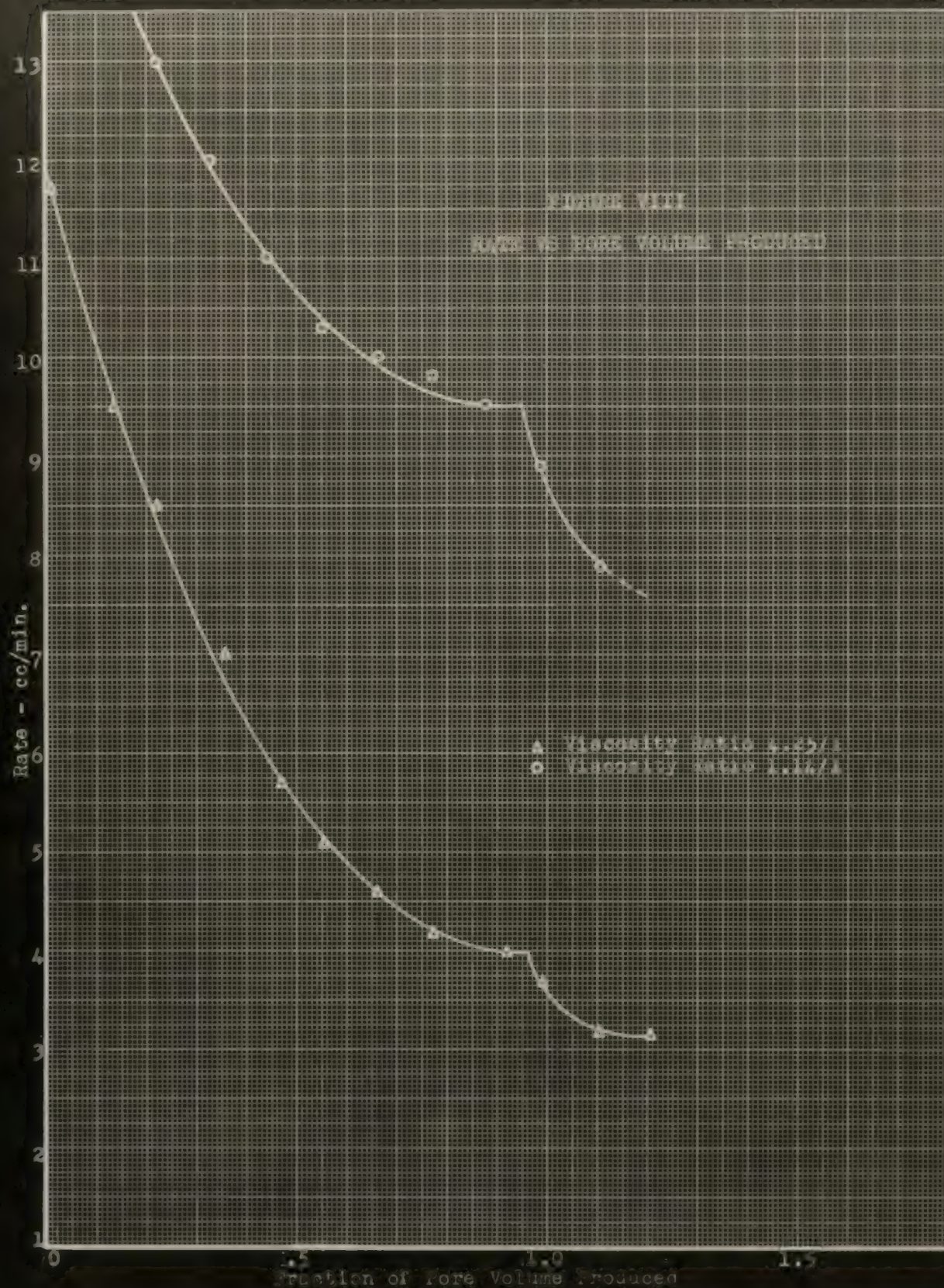
1.0

.5

0

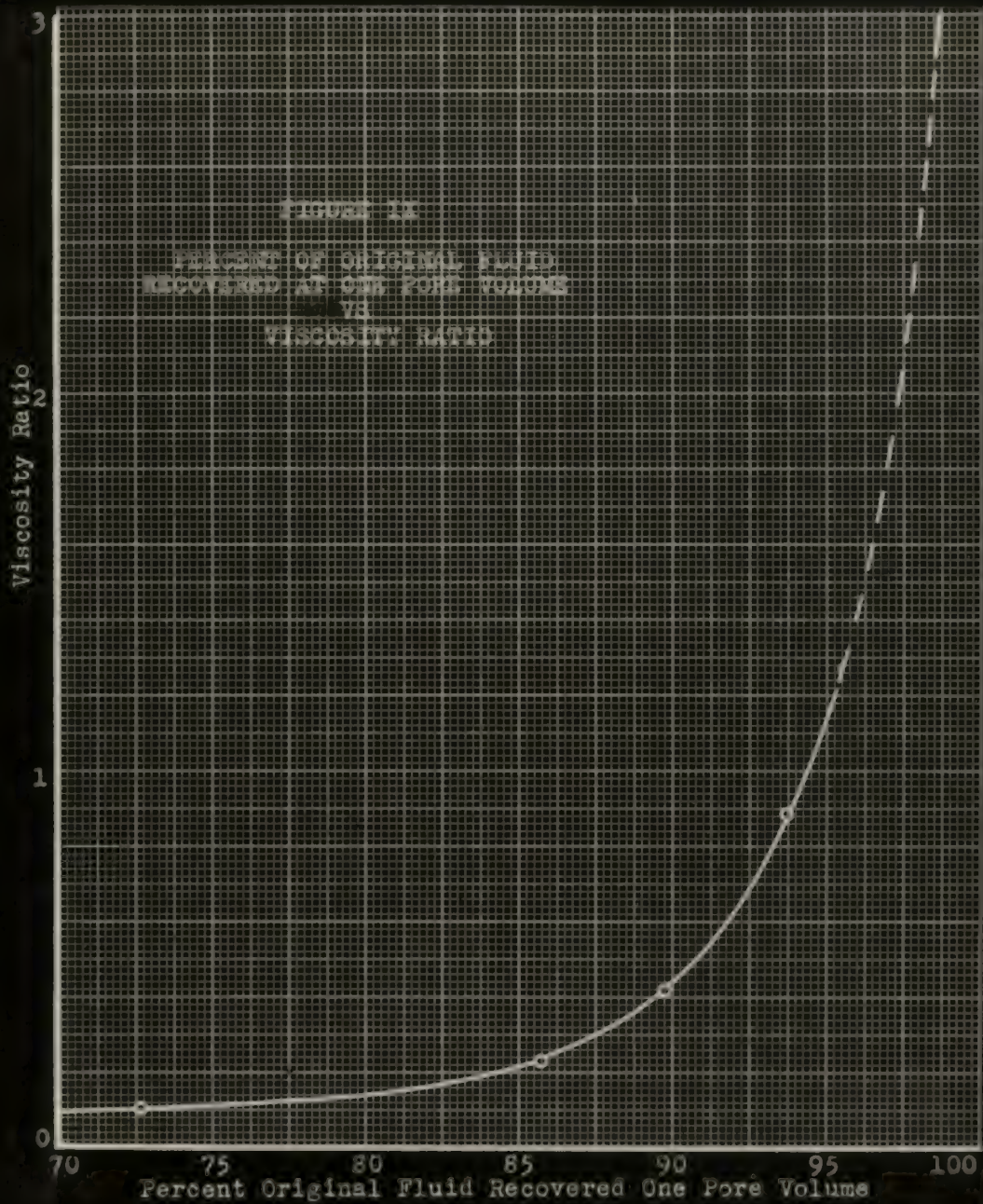






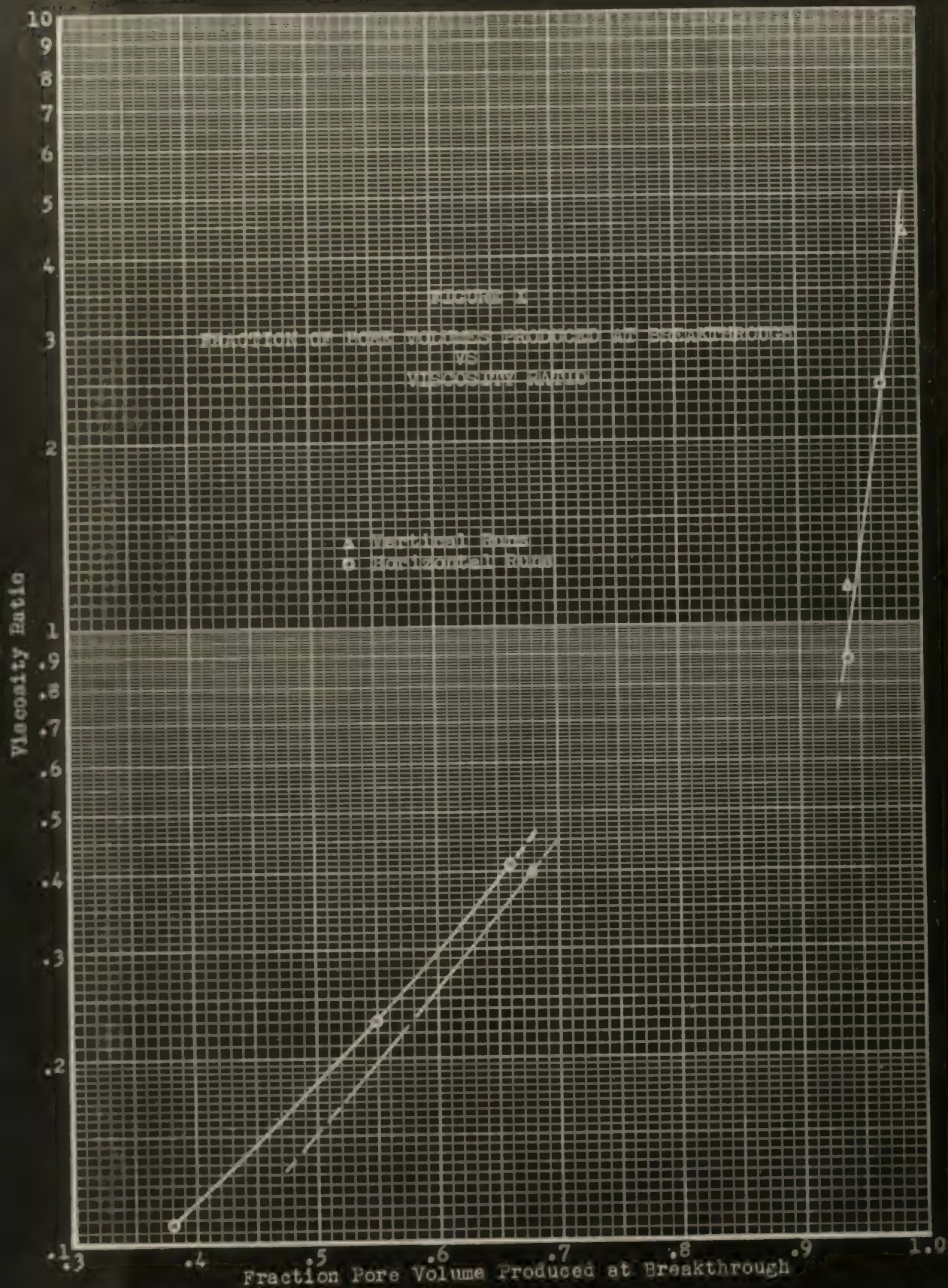






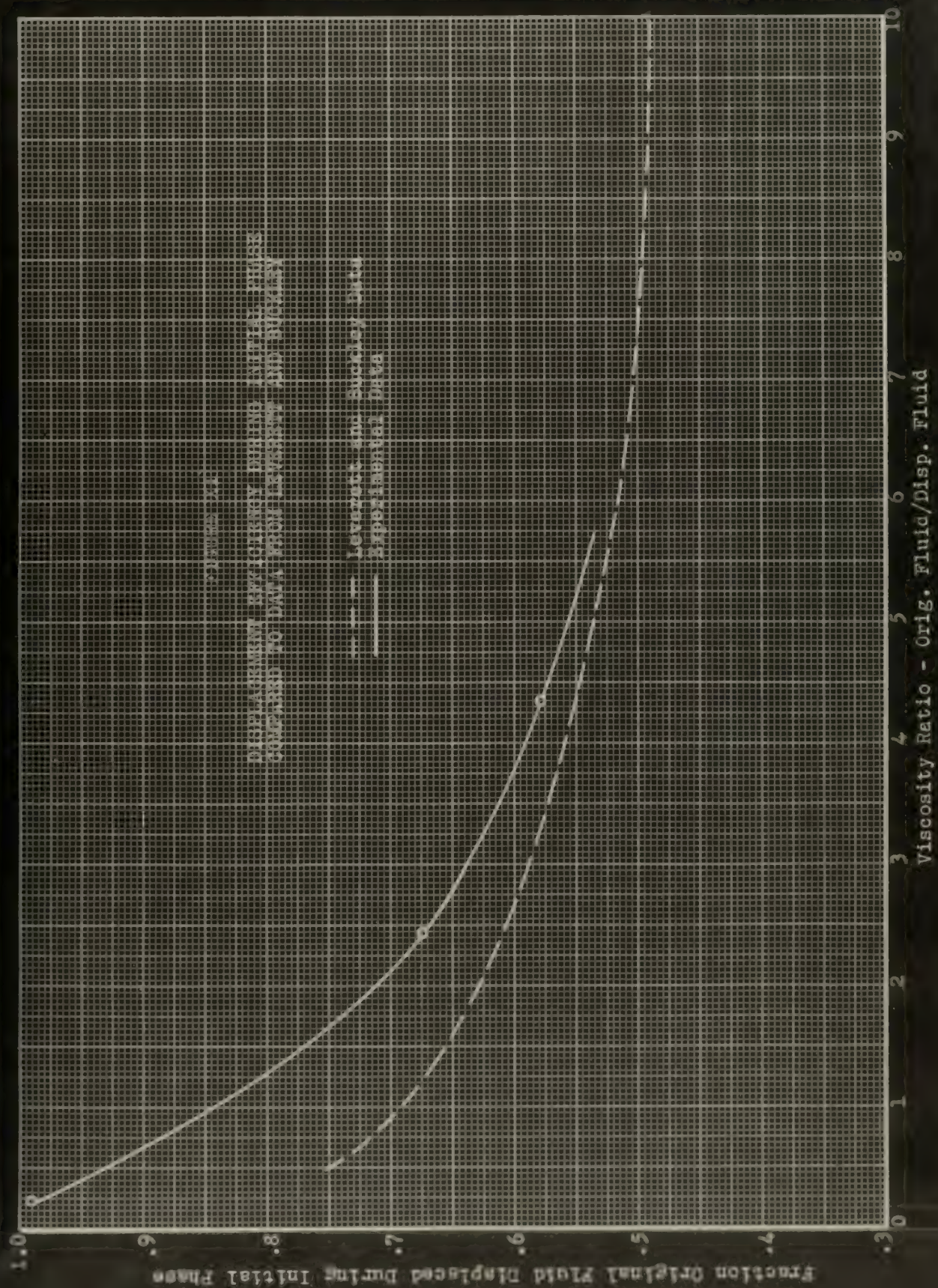






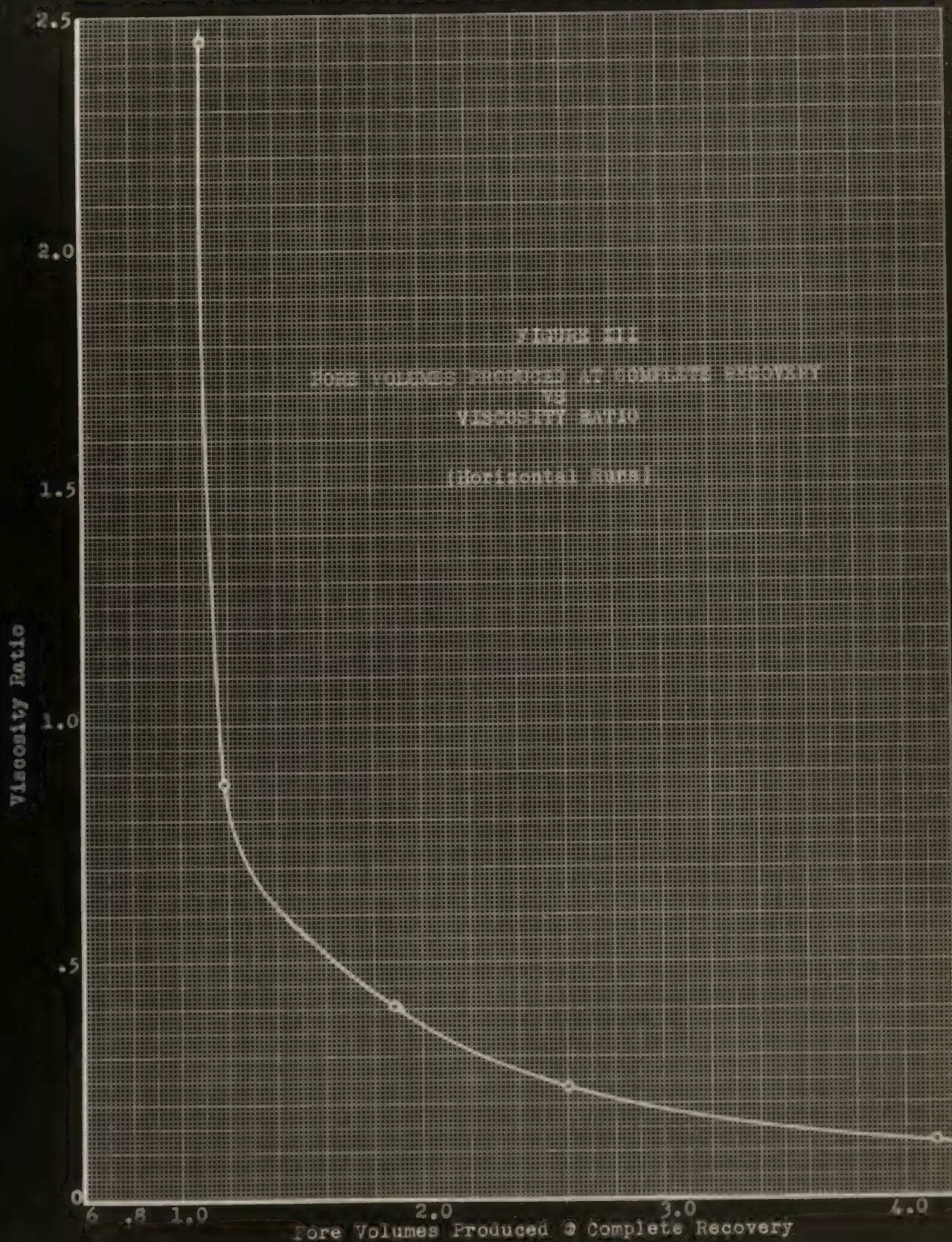






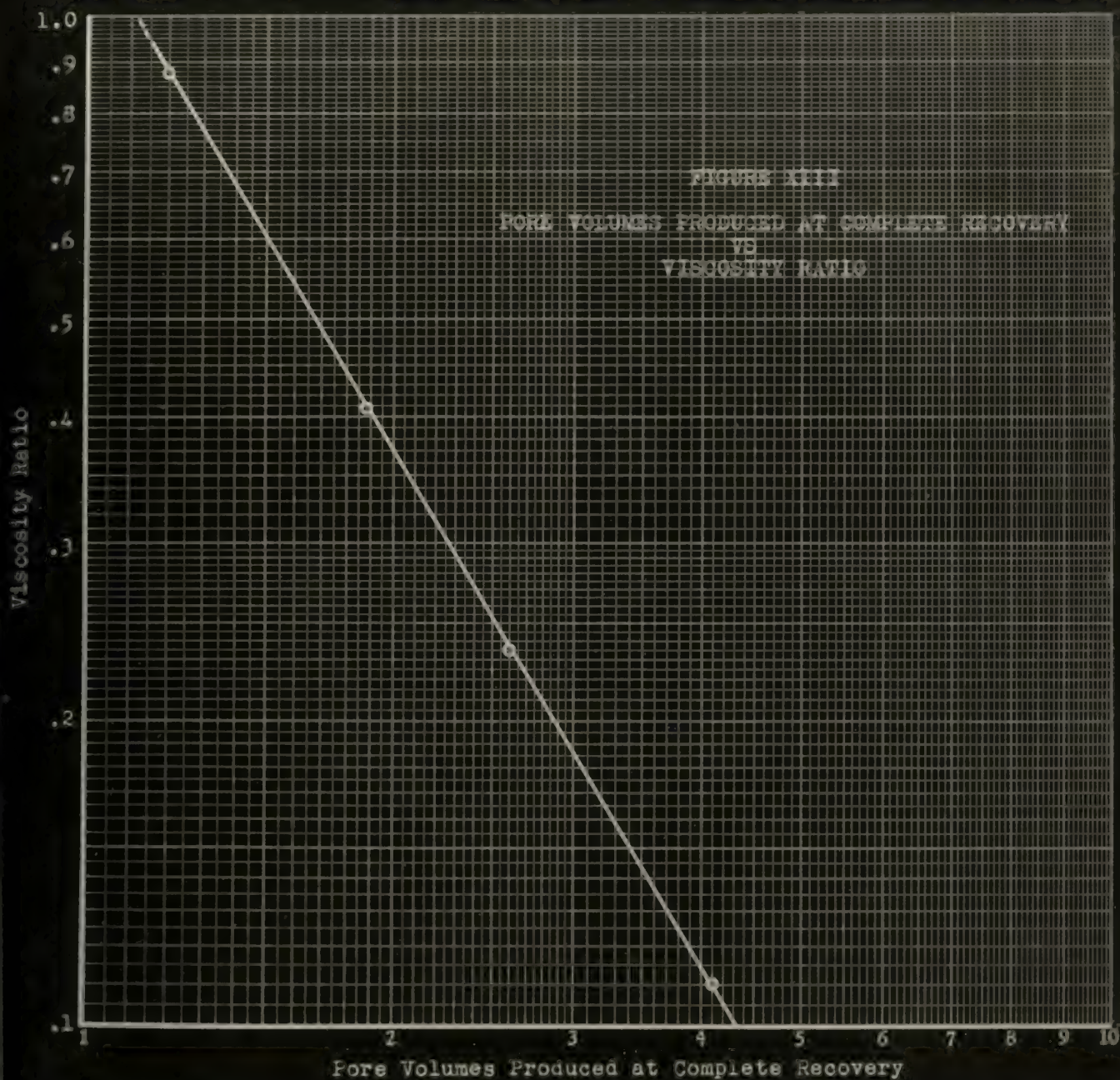






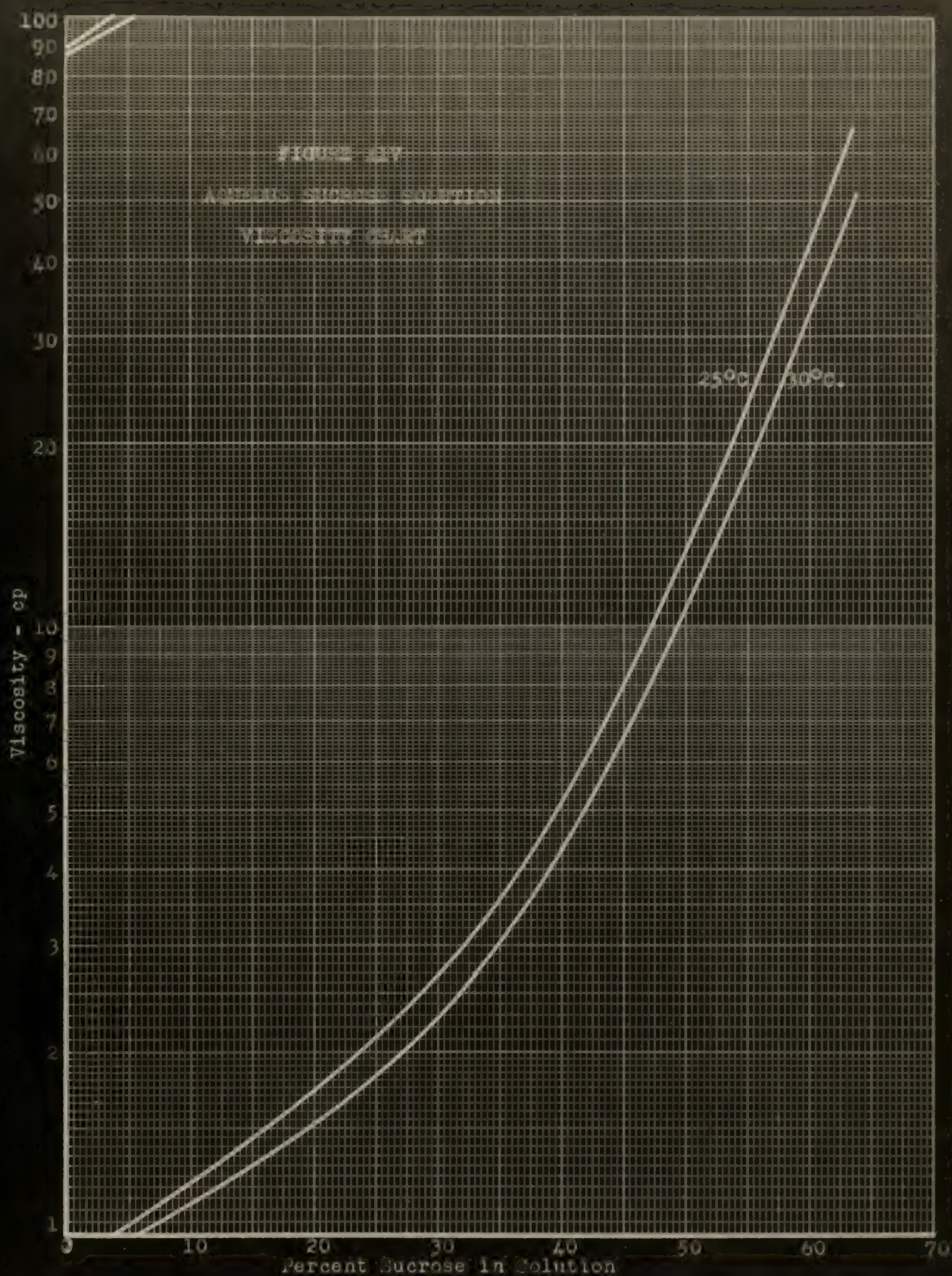














## CHAPTER VII

### ANALYSIS OF DATA

#### Theoretical Approach

An equation expressing the behavior of two miscible fluids at different viscosities, in the case of linear displacement, has been derived by Muskat (15). In developing this equation he simplified the system to one in which the two fluids are moving in a channel of great extent that is small compared to its length. This would be represented physically by a narrow channel of high permeability. Figure 1 illustrates such a linear system.

For a system as shown in Figure 1 Muskat derives the following equation:

$$\left(\frac{P_2}{P_1} - 1\right) \left[ \frac{P_2}{\mu} (1 - \epsilon) + \epsilon + 1 \right] \frac{2\Delta\phi C}{L^2} = 0; \quad \text{Equation (1)}$$

where:  $k$  = permeability

$p$  = pressure

$\phi$  = potential function =  $h_p$  if gravity is neglected

$\mu$  = viscosity

$\epsilon$  = fluidity =  $1/\mu$

$L$  = length





$t$  = time

$\Delta\phi$  = difference in potential function existing at the two boundaries.

$$\epsilon = \frac{c}{c_2} = \frac{\mu_2}{\mu_1}$$

$x$  =  $l$  minus distance flood front has traveled.

Since  $\epsilon$  is included in the combined term  $\frac{\epsilon \Delta\phi c_1 t}{L^2} = 0$ , it shows that at any particular state of the displacement the time necessary to reach this state varies directly with the viscosity of the displaced fluid, directly as the total length of the system and inversely as the average potential gradient  $\frac{\Delta\phi}{L}$ . From this it is seen that as the interface advances its rate of advance is accelerated if the displacing fluid has the higher fluidity ( $\epsilon < 1$ ) whereas it is retarded if the displacing fluid has the lower fluidity ( $\epsilon > 1$ ).

The total time for the interface to travel the total length is given by setting  $x_0$  equal to zero in equation one and solving for  $t_{max}$ .

$$t_{max} = \mu_1 (1 + \mu_2/\mu_1) \frac{fL^2}{2\Delta\phi} \quad \text{Equation (2)}$$

where  $f$  is the porosity of the section.

From this relation it is evident when  $\mu_2 < \mu_1$  the displacement time is less than that for a single fluid.

$$t_{max}^0 = \frac{\mu_1 fL^2}{\Delta\phi} \quad \text{Equation (3)}$$

It may also be noted that when  $\mu_2$  is very much smaller than

Let  $\Delta$  be the area of the triangle  $ABC$ . Then  $\Delta = \frac{1}{2}bc \sin A$ .

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$$

Let  $\Delta$  be the area of the triangle  $ABC$ . Then  $\Delta = \frac{1}{2}bc \sin A$ .

$$\Delta = \frac{1}{2}bc \sin A = \frac{1}{2}ac \sin B = \frac{1}{2}ab \sin C$$

Let  $\Delta$  be the area of the triangle  $ABC$ . Then  $\Delta = \frac{1}{2}bc \sin A$ .

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$$\frac{a^2}{\sin A} = \frac{b^2}{\sin B} = \frac{c^2}{\sin C}$$

Let  $\Delta$  be the area of the triangle  $ABC$ . Then  $\Delta = \frac{1}{2}bc \sin A$ .

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$$\frac{a^2}{\sin A} = \frac{b^2}{\sin B} = \frac{c^2}{\sin C}$$

Let  $\Delta$  be the area of the triangle  $ABC$ . Then  $\Delta = \frac{1}{2}bc \sin A$ .

$\mu_1$  a maximum decrease in  $t_{app}$ . is attained, then in this limiting case the drive by a displacing fluid of very low viscosity would cut by half the time required for the volume of original fluid to pass through the system. When  $\mu_2 > \mu_1$  it can be seen that  $t_{app}$  will always exceed  $t_{app}^0$ , and will ultimately become infinite as  $\mu_2$  becomes infinitely large.

### Sample Calculations

In all of the experiments the only physical properties of the solutions measured were temperature and index of refraction. From these two measurements could be calculated the amount of sucrose in the solution and thus the fraction of the original fluid in the effluent stream.

As an example one calculation is shown for converting the index of refraction to fraction of original fluid in the effluent. Data is taken from Run No. 3, Table III, when 500 cc of fluid had been displaced.

Taking the index of refraction 1.0000 at 20° C, for the original fluid in the case, and referring to the table, "Index of Refraction of Aqueous Solutions of Sucrose," in the Handbook of Chemistry and Physics, the per cent of sucrose was determined for a temperature of 20° C. to be 14.5. A temperature correction of + .43 was applied giving a per cent by weight of 14.93. From the table, "Specific Gravity of Aqueous Sucrose Solutions," in the same reference it was determined that this per cent of sucrose equals 341.3 grams per liter.

1. The first part of the document is a list of names and dates, which appears to be a record of some kind. The names are written in a cursive script, and the dates are in a more formal, printed style. The list is organized into two columns, with names on the left and dates on the right.

2. The second part of the document is a series of handwritten notes or entries. These are written in a cursive script, similar to the names in the first part. The notes are organized into a list, with each entry starting with a number or letter.

3. The third part of the document is a series of handwritten notes or entries, similar to the second part. These are also written in a cursive script and are organized into a list.

4. The fourth part of the document is a series of handwritten notes or entries, similar to the previous parts. These are written in a cursive script and are organized into a list.

5. The fifth part of the document is a series of handwritten notes or entries, similar to the previous parts. These are written in a cursive script and are organized into a list.

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10. The tenth part of the document is a series of handwritten notes or entries, similar to the previous parts. These are written in a cursive script and are organized into a list.

1875



When 500 cc of fluid had been displaced from the core the index of refraction of the effluent was measured and found to be 1.3329 at a temperature of 25° C. From the Handbook of Chemistry and Physics the corrected per cent of sucrose was determined to be 18.35 and the weight of sucrose in grams per liter 100. To get the fraction of the original fluid present in the effluent stream the following relation is used:

Fraction of Orig. Fluid in Eff. =  $\frac{\text{g./litr. sucrose in effluent}}{\text{g./litr. sucrose in orig. fluid}}$   
 Substituting the above values gives:

$$\text{Frac. of Orig. Fluid in Eff.} = \frac{100.0}{111.5} = .896$$

### DISCUSSION OF EXPERIMENTAL RESULTS

The results obtained in this series of experiments are tabulated in Tables I through XII. These tables have been simplified by including only the pertinent data. In addition the original data contained index of refraction of the total solution displaced and total elapsed time, which were not used in this work. In Runs 1 through 3 the rate of flow was not recorded and in Run 4 the screen at the inlet end of the core became plugged and thus the rates recorded during this run were of no benefit.

All runs were made with the core in a horizontal position except runs number 5, 7, 8, 9. The core was placed in a vertical position for these runs. When a heavy fluid was displaced by a lighter fluid, the lighter fluid was introduced at the upper end of the core; if a light fluid was being displaced

On the 1st of January 1900 the following was received from the

Director of the Census Bureau, Washington, D.C.

For the purpose of the Census of 1900 it is requested that you

will cause to be prepared a list of the names of all persons

who were born in the United States and who are now residing

in the State of New York, and who are of the age of 18 years or

more on the 1st of January 1900.

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by a heavier fluid it was introduced at the lower end of the core. Thus it was felt that the results of these drives were free from all effects of gravity.

Figures III and IV illustrate graphically the results of slight runs carried out at various viscosity ratios. Viscosity ratio as used in this paper will be the viscosity of the displacing fluid divided by the viscosity of the original fluid unless otherwise noted.

Figure III presents the results of the horizontal runs for various viscosity ratios. When the viscosity ratio is small as shown by the plot for a viscosity ratio of 1/3.2 the displacing fluid breaks through before half a pore volume has been produced. Following this break through there is a fairly constant decrease in the amount of original fluid in the effluent until approximately .8 of a pore volume is produced. From this point to a production of 1.6 pore volumes there appears to be unstable production conditions as evidenced by the scattered points on the plot. The curve then tends to level off with very slight decrease in the amount of original fluid in the effluent. This appears to form a plateau on the plot. It is possible that this could be caused by gravity segregation since there was definite evidence of this when the progress of the fluid front was followed visually as it moved along the core. The heavier fluid appeared to channel along the bottom of the core. When the core was rotated to check the possibility that the permeability was greater along







one side of the tube, the channeling effect was still along the bottom indicating that it could be caused by gravity.

Referring again to Figure III when the viscosity ratio approached unity or larger, as illustrated by the plot for a ratio of 1/1.14, the displacing fluid does not break through until over .8 of a pore volume is produced. The amount of original fluid in the effluent drops off rapidly with no apparent plateau in the curve. This should follow if the plateau is due to gravity segregation.

Similar runs were made with the core in a vertical position and the results plotted in Figure IV. From this it can be seen that the fraction of original fluid produced at break through is essentially the same as in the horizontal runs and thus is not appreciably affected by gravity. There was no indication of a plateau with a viscosity ratio as low as 1/4.22 which bears out the supposition that this leveling off, in the cases illustrated in Figure III, was caused by gravity segregation.

From Figures III and IV it would appear that the mechanics of displacement involving two miscible fluids is similar to that of two immiscible liquids as described by Buckley and Leverett (10). The displacement can be divided into two phases. The initial phase occurs before the break through of the displacing fluid and is a piston like displacement. In the subsequent phase, which follows the break through, the original fluid is produced by a dragging action.



This phase differs in the case of miscible fluids only in that 100 per cent of the original fluid can be produced which is not possible with immiscible fluids.

As a check on the accuracy of the plots and on the completeness of recovery of the original fluid from the core the area under each curve was measured. With 100 per cent recovery of the original fluid the area under each curve should be 100 units. In all cases the error was never more than 2 per cent.

The cause of the period of unstable production is not known, though it would seem possible that it would be due to streaks of variable permeability which would allow by-passing of small areas. At a later time the original fluid from these areas would reach the outlet end of the core and temporarily increase the amount of original fluid in the effluent.

To see what effect pressure would have on the displacement picture two runs were made using a viscosity ratio of 1/2.44. The pressure differential for one run was 250 mm. mercury and for the other run was 700 mm. mercury. The results plotted in Figure 5 show that as pressure tends to cause a break through to occur earlier and to require more pore volumes before complete displacement of the original fluid takes place.

To study the possible effects of gravity segregation, runs were made with the core both in the horizontal and







vertical position. Two runs with a viscosity ratio of 1/2.15 were plotted in Figure VI. From this plot it can be seen that in the horizontal run where it is possible for gravity segregation to take place the curve is not as simple or smooth as the curve for the vertical run. However, the vertical run does break through earlier than the horizontal run, but the plateau shown up in the horizontal run thus requiring more pore volumes through-pot before complete displacement takes place.

Though it is not included herein, a similar plot for a viscosity ratio of 1/2.16 shows similar deviations between the two curves.

According to Masati (15) the effect of viscosity ratio on the rate of flow of the effluents can be calculated by Equation (1). If the original fluid is being displaced by one of lower viscosity the overall resistance of the system will be lowered and the rate of effluents increased. If the original fluid is displaced by one of higher viscosity the overall resistance is increased and the rate of effluents decreased.

From Figure VII it is noted that there is an appreciable increase in effluent rate as seen at injection of the lower viscosity fluid somewhere. This increase in effluent rate tends to gradually drop off until the point is reached where the displacing fluid breaks through. Then there is a sharp increase in effluent rate with an immediate tapering off



of the rate till the point is reached where the original fluid is completely displaced and the efflux rate is constant.

This behavior is similar to the qualitative description given concerning the nature of the effects of the viscosity difference between surrounding and displaced liquids in the case of direct drives by Muskat (13). This should follow since the injection of the displacing fluid into a small opening in one end of a long cylindrical tube and producing from a small opening in the other end would in many ways approximate the physical conditions of a direct drive between two wells.

The same pattern is shown by Figure VIII except in this case the original fluid is being displaced by one of higher viscosity, thus there is a decrease in efflux rates in place of an increase. The curve for a viscosity ratio of 1.36/1 was affected by a flanging of the curves at the inlet end of the core during the run. However, it was included since it illustrates the qualitative description given by Muskat.

To indicate a measure of the efficiency of the various drives as a function of the viscosity ratio, Figures IX, X, and XI were constructed. Figure IX illustrates the efficiency of recovery when one pore volume of fluid has been displaced from the core. From this it can be seen that as the viscosity ratio becomes smaller than .5 the per cent of original fluids displaced, when one pore volume has been produced, falls off



The first of these is the fact that the majority of the population of the United States is of European descent. This is a fact which is often overlooked, and which is of great importance in understanding the social and economic conditions of the country. The second fact is that the majority of the population of the United States is of European descent. This is a fact which is often overlooked, and which is of great importance in understanding the social and economic conditions of the country. The third fact is that the majority of the population of the United States is of European descent. This is a fact which is often overlooked, and which is of great importance in understanding the social and economic conditions of the country.



rapidly. With the viscosity ratio unity or larger there is very little increase in the per cent of original fluid displaced. Thus it can be seen that as long as the viscosity ratio is .5 or greater 25 per cent or more of the original fluid will be displaced when one pore volume has been produced.

As another measure of the efficiency of displacement, the pore volume produced when the displacing fluid breaks through was plotted against the logarithm of the viscosity ratio in Figure 2. This plot appears to give a straight line up to a viscosity ratio of .4 with a break from this point to a viscosity ratio of approximately .8. At this point there was a return to linearity but at a new slope. Unfortunately runs were not made with viscosity ratios in the region of departure from linearity so that information on this region is missing. It would seem, as indicated by Figure 2, when the viscosity ratio is .8 or greater that the recovery efficiency would be very high.

Figure 3 shows a plot of pore volumes of original fluid produced during the initial phase versus viscosity ratio, where the viscosity ratio is equal to the viscosity of the original fluid divided by the viscosity of the displacing fluid. For comparison data given by Buckley and Leverett (10), concerning the effect of oil viscosity on the efficiency of the initial phase of a water flood in a typical sand, is also plotted in the same figure.

The shape of the two curves in the above plot is

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matter; however, the effect of viscosity ratio is greater in the case of miscible fluids. This might be explained by the fact that in the case of immiscible fluids all of the original fluid is not active and is not moved at any time during the displacement; thus limiting the range of the fraction of original fluid that could be displaced during the initial phase.

Figures III and IIII give the number of pore volumes required before complete recovery of the original fluid is obtained. Figure III indicates that the number of pore volumes required for complete recovery, for a viscosity ratio of .5 or greater, would be slightly larger than one. The number of pore volumes required as the viscosity ratio gets smaller does not decrease rapidly until a viscosity ratio of .6 is reached. From here the increase is very great even with only slight reductions in viscosity ratio.

The same data plotted on log paper gives a straight line with viscosity ratios of .5 or lower.

Referring to the article, "Some Experiments on the Possibility of Interstitial Waters" (12), where data is contained on the displacement from a sandstone core of radio active water by non active water the following conclusions are given: the displacing fluid breaks through when between .6 and .9 of a pore volume has been produced, 30 to 50 per cent of the original fluid was recovered when one pore volume had been produced, and over 1.5 pore volumes were produced before complete recovery of the original fluid occurs.







The data obtained during the present series of experiments, for a viscosity ratio comparable to that used in studying the results described above, does not show the above conclusions. This data indicates that over 90 per cent of the original fluid is produced before the displacing fluid breaks through, approximately 90 per cent of the original fluid is displaced when one pore volume has been produced, and less than 1.5 pore volumes are required for complete recovery of the original fluid.

Thus even greater mobility of the interstitial water is indicated than was shown in the previous experiment. This could be due to the higher permeability that undoubtedly existed in this experiment but it would not seem that this alone would account for this difference.

It would appear that the shape of the displacement curves, Figures III and IV could be useful in studying the mechanism of displacement. Equation 5 indicates that the shape of the displacement curves might be an indication of the degree of permeability variation present in the porous media. However, work done by Taylor and Brown (13) displacing one fluid by another in a pipe line indicates that the shape of the displacement curves is a result of the parabolic interface formed in case of the capillary spreading.

It would seem possible that the shape of the displacement curves could be affected by both of the above factors.

#### EXPERIMENTAL

The use of a refractometer to measure index of



refraction which in turn is converted to per cent of sucrose. In an aqueous solution limits the accuracy of the results to the accuracy of the instrument used. In this work a Spencer photo-type refractometer was used. The scales on it could be read directly to the third decimal place and the fourth estimated with an accuracy of 0.0001. This gave an accuracy of 0.2 per cent in measuring the per cent of sucrose in solution.

The accuracy of the refractometer was checked before any runs were made by use of the glass test slab included with the instrument for which the index of refraction was known.

Index of refraction and viscosity of the solutions are both affected by changes in temperature. Since the temperature seldom changed more than a degree during a series of measurements it was felt that any temperature effects were within the experimental error. No appreciable effects on the data were observed that could be attributed to changes in temperature.

A small error was certainly introduced in the measurement of pressure differential with a liquid manometer and volume displaced with a graduated cylinder since there is some known error in reading fluid levels. These readings are considered to be well within the range of experimental error and sufficiently accurate for the computations necessary in this work. The degree of accuracy of these readings is indicated by graphical integration of the areas under the curves shown in Figures III and IV. The majority of these areas were in error by less than one per cent and all were less than two per cent.







## CHAPTER VIII

### SUMMARY

A study was made of the displacement of one miscible fluid by another from a partially consolidated synthetic sandstone core. This core was composed of 20 to 100 mesh oil creek silica sand and colloidal silica. The porosity of the core was 36.7 per cent and the air permeability was 3.32 darcies. This core 2.55 centimeters in diameter and 13.7 centimeters in length was assembled with pressure taps in each end plate to permit determination of pressure drop across the core. The core was saturated with a fluid of known viscosity, then this fluid was displaced by another miscible fluid of different viscosity. The rate of efflux, total amount of fluid produced, and data to calculate the per cent of original fluid in the effluent was measured and recorded at regular intervals.

The solutions used in these experiments were made by dissolving various amounts of sand sugar (sucrose) in distilled water. The amount of sucrose in solution determined the viscosity of the fluid. Four solutions were used plus distilled water to get a range of viscosity ratios. The four

## THE STATE

It is the duty of the State to protect the rights of its citizens and to maintain the peace and order of the community. The State is responsible for the welfare of its people and for the preservation of its territory and resources. The State is also responsible for the education and training of its citizens and for the promotion of the economic and social progress of the nation. The State is the guardian of the public interest and the protector of the rights of the individual. The State is the source of the law and the enforcer of the law. The State is the representative of the people and the agent of their will. The State is the symbol of the unity and the strength of the nation. The State is the foundation of the civil society and the basis of the democratic system. The State is the guarantor of the rights and freedoms of the citizen and the defender of the common good. The State is the embodiment of the power and the authority of the people. The State is the center of the political life and the focus of the public attention. The State is the source of the legitimacy and the authority of the government. The State is the basis of the international relations and the representation of the nation in the world. The State is the symbol of the continuity and the stability of the society. The State is the foundation of the national identity and the source of the national pride. The State is the guardian of the cultural heritage and the promoter of the national development. The State is the protector of the environment and the defender of the natural resources. The State is the guarantor of the social justice and the promoter of the economic growth. The State is the source of the law and the enforcer of the law. The State is the representative of the people and the agent of their will. The State is the symbol of the unity and the strength of the nation. The State is the foundation of the civil society and the basis of the democratic system. The State is the guarantor of the rights and freedoms of the citizen and the defender of the common good. The State is the embodiment of the power and the authority of the people. The State is the center of the political life and the focus of the public attention. The State is the source of the legitimacy and the authority of the government. The State is the basis of the international relations and the representation of the nation in the world. The State is the symbol of the continuity and the stability of the society. The State is the foundation of the national identity and the source of the national pride. The State is the guardian of the cultural heritage and the promoter of the national development. The State is the protector of the environment and the defender of the natural resources. The State is the guarantor of the social justice and the promoter of the economic growth.

solutions contained 4.1, 14.3, 22.2, and 45.00 per cent of sucrose by weight.

Since information of a fundamental nature was sought it was decided to vary only the viscosity ratio of the displaced fluid to the original fluid and to maintain all other factors as nearly constant as possible. The range of viscosity ratios studied in these experiments ran from .11 to 5.1.

The data gathered in this work was used to arrive at several conclusions regarding the effect of viscosity ratio on the mechanics and the efficiency of displacement of one miscible fluid by another.

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## CHAPTER IX

### CONCLUSIONS

1. The mechanism of the displacement of one miscible fluid by another is similar to the mechanism of displacement where the two fluids are immiscible. The displacement can be divided into two phases, the initial phase where there is a piston like displacement and the subsequent phase where the fluid is displaced by a dragging action.

2. When the viscosity ratio is smaller than unity the rate will decrease, if the viscosity ratio is larger than unity the rate will increase.

3. Increasing pressure differential and maintaining the same viscosity ratio causes the break through of the displacing fluid to occur earlier and requires more pore volumes to obtain complete displacement of the original fluid.

4. If gravity segregation is present more pore volumes will be required to obtain complete recovery.

5. Efficient displacement in the initial phase is obtained with viscosity ratios of .4 or greater. More than 80 per cent of the original fluid is recovered when one pore volume has been produced.



6. For the most efficient complete recovery of original fluids the viscosity ratio should be .5 or greater.

7. Viscosity ratios of .5 and lower do not produce efficiently in the initial phase and require 2 or more pore volumes for complete recovery.

8. There is very little increase in the efficiency of displacement when the viscosity ratio is increased beyond unity.

9. Further study is desirable if a relation exists between the shape of the displacement curves and permeability variation is indicated in view of the importance of this factor in the production of petroleum.

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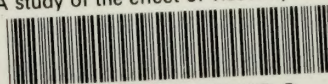






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